Pratt & Whitney Aircraft
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MANUFACTURING TECHNIQUES AND MATERIALS (U).

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CONTENTS

PREFACE
MANUFACTURING TECHNIQUES AND MATERIALS

This report covering manufacturing techniques and materials to be used for hardware components of the JTF17 engine for Phase III is comprised of four parts, as follows:

TABULATION OF MATERIALS SPECIFIED

One table lists the materials specified for hardware components for the JTF17 engine. A second table, which is a cross indexed tabulation of materials listed in the first table, shows usage of these materials in current P&WA engines. As can be seen from this second table, all the materials selected for the JTF17 are used in current engines, eliminating the risk associated with development of sources, processes, and quality control of new unproved materials.

~~SECTION I —~~ MATERIALS PROCESSING AND FABRICATION TECHNIQUES

This section describes advanced manufacturing development, process improvement during experimental manufacturing and production, and the process control system. Processing and fabrication techniques developed for the manufacture of hardware for the advanced supersonic J58 engine that will be utilized for manufacture of JTF17 components are described. Process control is emphasized and illustrated by four alloy groups, five major components for the JTF17 engine, and twelve metallurgical and chemical processes. Development application of new processes to reduce cost and improve availability and reproducibility are also discussed.

~~SECTION II —~~ ANALYSIS OF MATERIALS SPECIFIED AND PROPOSED

This section analyzes the use of materials "Specified" in the "Tabulation of Materials" for the JTF17 engine. Particular emphasis has been placed upon those materials which are to be used for the most critical hardware components; viz, fan and high compressor blades and disks, and turbine vanes, blades, and disks. The extensive work accomplished by P&WA in developing many of these materials to satisfy the most demanding requirements of the supersonic cruise J58 engine is described. This section also analyzes the use of "Proposed" (advanced) materials for ultimate improvement in engine performance and life, and reduction in engine weight and cost.

and Section III - Specified coatings and description of coating processes.

SECTION III - SPECIFIED COATINGS AND DESCRIPTION OF COATING PROCESSES

This section discusses coatings "Specified" in Section I for the JTF17 engine for improvement of the life of turbine blades and vanes. These coatings, which were developed for the J58 engine, are discussed in detail, including their inherent characteristics, the methods of application used, and their behavior in conjunction with the basis material as determined by laboratory rig and micro-structural examination.

In addition to "Specified" coatings, advanced coating development for improved blade and vane life is described.

TABULATION OF MATERIALS SPECIFIED

Unless otherwise noted all materials listed apply to both prototype and production engine designs.

1. Table 1 is a tabulation of specified materials that are designated on the Engineering Drawings for the major components for the JTF17 engine.
2. Table 2 is a cross-index tabulation of the materials listed in Table 1, showing usage of these materials in current P&WA engines.

Table 1. Specified Materials for the Major Components for the JTF17 Engine

Engine Section	Part Name	Material Specification	Alloy Type
Fan			
	Case	AMS 4966	A-110AT
	Mount Ring	AMS 4966	A-110AT
	Bolts	PWA 1010	Inco 718
	1st Blade	AMS 4928	Ti-6Al-4V
	2nd Blade	AMS 4928	Ti-6Al-4V
	1st Disk	AMS 4928	Ti-6Al-4V
	2nd Disk	PWA 1202	Ti-8Al-1Mo-1V
	1st Vane	AMS 4928	Ti-6Al-4V
	2nd Vane	AMS 4928	Ti-6Al-4V
	Duct Exit Guide Vane	AMS 4928	Ti-6Al-4V
	Shaft	PWA 1003	Incoloy 901

Table I. Specified Materials for the Major Components for the JTF17 Engine (Continued)

Engine Section	Part Name	Material Specification	Alloy Type
Intermediate Case			
	Case	AMS 4910	A-110AT
	1st and 2nd Bearing Supports	AMS 5667	Inconel X
	1st and 2nd Cages	AMS 6414 or AMS 6415	Low Alloy Steel
	1st and 2nd Bearings and Races	PWA 725 (Ball)	M-50
	Aerodynamic Brake	PWA 1202	Ti-8Al-1Mo-1V
High Compressor			
	3rd Blade	PWA 1202	Ti-8Al-1Mo-1V
	4th Blade	PWA 1202	Ti-8Al-1Mo-1V
	5th Blade	PWA 1202	Ti-8Al-1Mo-1V
	6th Blade	PWA 1016	Waspaloy
	7th Blade	PWA 1016	Waspaloy
	8th Blade	PWA 1016	Waspaloy
	Front Hub	PWA 1003	Incoloy 901
	3rd Disk	PWA 1016	Waspaloy
	4th Disk	PWA 1016	Waspaloy
	5th Disk	PWA 1016	Waspaloy
	6th Disk	PWA 1016	Waspaloy
	7th Disk	PWA 1016	Waspaloy
	8th Disk	PWA 1016	Waspaloy
	Rear Hub	PWA 1016	Waspaloy
	Knife Edge Seals	PWA 1016	Waspaloy
	3rd Vane	PWA 1202	Ti-8Al-1Mo-1V
	4th Vane	PWA 1202	Ti-8Al-1Mo-1V
	5th Vane	PWA 1010	Inco 718
	6th Vane	PWA 1010	Inco 718
	7th Vane	PWA 1010	Inco 718
	Exit Guide Vane	PWA 1010	Inco 718
	3rd Case	AMS 4910	A-110AT
	4th Case	AMS 4910	A-110AT
	3rd and 4th Knife Edge Seal Lands	AMS 5616	Greek Ascoloy
	5th Case	PWA 1009	Inco 718
	6th Case	PWA 1009	Inco 718
	7th Case	PWA 1009	Inco 718
	8th Case	PWA 1009	Inco 718
	5th, 6th, 7th and 8th Knife Edge Seal Lands	AMS 5754	Hastelloy X
	Tie Bolts	PWA 1016	Waspaloy
Main Diffuser Case			
	Flanges, Rings and Struts	PWA 1009	Inco 718
	Case Sheet Material	AMS 5596	Inco 718
	Splitter	AMS 5754	Hastelloy X

Table 1. Specified Materials for the Major Components for the JTF17 Engine (Continued)

Engine Section	Part Name	Material Specification	Alloy Type
Main Burner			
	Fwd. Outer Cases	AMS 5596	Inco 718
	Fwd. Inner Case	AMS 5596	Inco 718
	Rear Outer Case	AMS 5596	Inco 718
	Rear Inner Case	AMS 5596	Inco 718
	Burner	AMS 5536	Hastelloy X
	Transition Duct	AMS 5536	Hastelloy X
No. 3 Bearing Support			
	Bearing Support	AMS 5613	AISI 410
	Support Cone	PWA 1009	Inco 718
	Knife Edge Seal		
	Lands and Supports	AMS 5754	Hastelloy X
	Cage	AMS 6414 or AMS 6415	Low Alloy Steel
	Bearings	PWA 742	Bower 315
Turbine			
	Cases (Fwd. and Rear)	PWA 1004	Waspaloy
	1st Blade	PWA 658 (PWA 64)	IN 100 (Coated)
	2nd Blade	PWA 658 (PWA 64)	IN 100 (Coated)
	3rd Blade	PWA 658 (PWA 64)	IN 100 (Coated)
	1st Disk	PWA 1013	Astroloy
	2nd Disk	PWA 1013	Astroloy
	3rd Disk	PWA 1013	Astroloy
	1st Vane	PWA 1035 (PWA 62)	TD Nickel
	2nd Vane	PWA 658 (PWA 64)	IN 100 (Coated)
	3rd Vane	PWA 658 (PWA 64)	IN 100 (Coated)
	Spacer	PWA 1003	Inco 901
	Bolts	PWA 93	Astroloy
Turbine Exhaust			
	Fwd. Outer Case	AMS 5544	Waspaloy
	Fwd. Inner Case	AMS 5544	Waspaloy
	Rear Outer Case	AMS 5544	Waspaloy
	Rear Inner Case	AMS 5536	Hastelloy X
	Exit Guide Vanes	PWA 655	Inco 713
No. 4 Bearing Support			
	Support Cone	AMS 5544	Waspaloy
	Housing	AMS 5613	AISI 410
	Cage	AMS 6414	Low Alloy Steel
	Bearings	PWA 742	Bower 315

Table 1. Specified Materials for the Major Components for the JTF17 Engine (Continued)

Engine Section	Part Name	Material Specification	Alloy Type
Fan Duct			
	Duct Diffuser	AMS 4910	A-110AT
	Diffuser	AMS 4910	A-110AT
	Duct Burner Support	PWA 1202	Ti-8Al-1Mo-1V
	Intermediate Outer Duct Case	PWA 1010 or AMS 5596	Inco 718
	Inner Access Panel	AMS 5596	Inco 718
	Fwd. Inner Duct	AMS 5536	Hastelloy X
	Rear Inner Duct	AMS 5536	Hastelloy X
	Front Screech Liner	AMS 5536	Hastelloy X
	Rear Screech Liner	AMS 5536	Hastelloy X
	Intermediate Cooling Liner	AMS 5536	Hastelloy X
	Rear Cooling Liner	AMS 5536	Hastelloy X
	Rear Mount Case	PWA 1010 or AMS 5596	Inco 718
Duct Heater			
	Birdcage	PWA 1202	Ti-8Al-1Mo-1V
	Duct Burner	AMS 5536	Hastelloy X
	Fan Exhaust Nozzle	AMS 5537	L-605
	Fan Nozzle Flaps	PWA 658	IN 100
Reverser-Suppressor			
	Tail Feathers	AMS 5536	Hastelloy X
	Clamshells	AMS 5536	Hastelloy X
	Outer Rear Skin	AMS 4916	Ti-8Al-1Mo-1V
	Rear Ring	PWA 1202	Ti-8Al-1Mo-1V
	Inner Rear Skin	AMS 4916	Ti-8Al-1Mo-1V
	Stings Inner Skin	AMS 4916	Ti-8Al-1Mo-1V
	Stings Outer Skin	AMS 4916	Ti-8Al-1Mo-1V
	Stings Frame Work	AMS 4916	Ti-8Al-1Mo-1V
	Intermediate Ring	PWA 1202	Ti-8Al-1Mo-1V
	Front Ring	PWA 1202	Ti-8Al-1Mo-1V
	Mount Ring	PWA 1202	Ti-8Al-1Mo-1V
	A-Frames	PWA 1202	Ti-8Al-1Mo-1V
Throughout Engine			
	Rivets	AMS 7235	A-286
		AMS 7232	Inconel
		AMS 7236	L-605
		AMS 7236	Hastelloy X
		AMS 4928	Ti-6Al-4V

Table 1. Specified Materials for the Major Components for the JTF17 Engine (Continued)

Engine Section	Part Name	Material Specification	Alloy Type
	Gears	PWA 724 and PWA 742	Bower 315
	Bolts (Nonrotating)	AMS 7471	Waspaloy
	Plumbing	PWA 1060	Inconel
		PWA 770	AISI 347 SS
	Oil Tank	AMS 5517	AISI 321 SS
Main Gearboxes			
	Housings	AMS 4910 and AMS 4928	Fabricated Ti-6Al-4V
	Shafts	PWA 724 and PWA 742	Bower 315
	Bearings	PWA 725	M-50
		PWA 742	Bower 315

Table 2. Specified JTF17 Engine Materials Used in Current P&WA Engine Applications

Alloy Class	Alloy Type	Material Specification	Experimental and Production Applications	Major Component in JTF17 Engine
Titanium Base	Ti-8Al-1Mo-1V	PWA 1202	TF30, J52, J58, JT8D	Fan Disk Compressor Blade Compressor Vanes
				Reverser Suppressor
	A-110AT	AMS 4910	All current models	Fan Vanes Fan Cases and Ducting
	Ti-6Al-4V	AMS 4928	JT8D, JT3D	Fan Blades, Fan Vanes, Fan Disk
Nickel Base	Waspaloy	PWA 1004 PWA 1005 PWA 1007 PWA 1016 AMS 5544	J58, TF30, TF33, JT3D, JT12	Turbine Cases Compressor Blades Rotor Shafts Compressor Disks
	Inco 718	PWA 1010	J58, TF30	Compressor Vanes and Cases
		AMS 5596		Main Diffuser Case Burner Case
	IN 100	PWA 658	J58	Turbine Vanes Duct Nozzle Flaps Turbine Blades

Table 2. Specified JTF17 Engine Materials Used In Current P&WA Engine Applications (Continued)

Alloy Class	Alloy Type	Material Specification	Current Engine Application	Major Component in JTF17 Engine
	Hastelloy X	AMS 5536	All current models	Main and Duct Burner
	Inco 713	PWA 655	J58, JT8D, J52, TF30, J75	Exit Guide Vanes
	Astroloy	PWA 1013	J58	Turbine Disks
	TD Nickel	PWA 1035	J58, TF30, JT8D	Turbine Vanes
	Incoloy 901	PWA 1003	All current models	Fan Shaft Compressor Rear Hub
Low Alloy Steels	Bower 315	PWA 724 & PWA 742	J58, JT3D, JT8D, TF30	Gears Roller Bearings
	M-50	PWA 725	J58, JT8D, TF30, JT3D	Ball Bearings
		AMS 6414 (Premium Quality AMS 6415)	J58, JT8 JT4, TF30	Bearing Cages
	AISI 410	AMS 5613	All current models	Bearing Housings

SECTION I
MATERIALS PROCESSING AND FABRICATION TECHNIQUES

A. INTRODUCTION

Pratt & Whitney Aircraft's experience in design, development, and production of the J58 engine has led to the development of new materials, processing and fabrication techniques and quality control practices which are directly applicable and essential to the SST engine. This section describes how P&WA will apply these techniques to the Phase III program.

This section is divided into five parts. In Part A, the manufacturing system is discussed from the initiation of advanced manufacturing development through the establishment of written production methods with appropriate manufacturing controls. Specific controls for various alloy systems (i.e., titanium alloys, nickel base alloys) are presented in Part B. Control of the processes used in manufacturing (i.e., types of welding, types of brazing) is described in Part C. Part D gives examples of the manufacturing system by explaining the production of typical Phase II-C JTF17 components. Part E presents some advanced developments of the various P&WA manufacturing groups with references to related metallurgical efforts.

P&WA has produced a large number of complicated weldments in age hardenable nickel base alloys of Waspaloy and Inconel 718. Figures 1 and 2 illustrate the complexity of these assemblies. These alloys are available in all forms for engine hardware and are readily manufactured and repaired after engine service by overhaul shops when established manufacturing procedures are followed. Figure 26 in Section II illustrates a weldment produced from Astroloy sheet. This alloy is also used for turbine disks. P&WA has developed techniques and processing for handling Astroloy welding, heat treating, and machining; see Section II, paragraph D3.

Directionally solidified castings offer bow and crack as well as thermal shock resistance advantages over conventional castings. As the result of successful engine development testing, directionally solidified castings are being utilized in the J58 and will be utilized in the JTF17. Figure 47 in Section II compares the grain size and shape of directionally solidified castings and conventional castings.

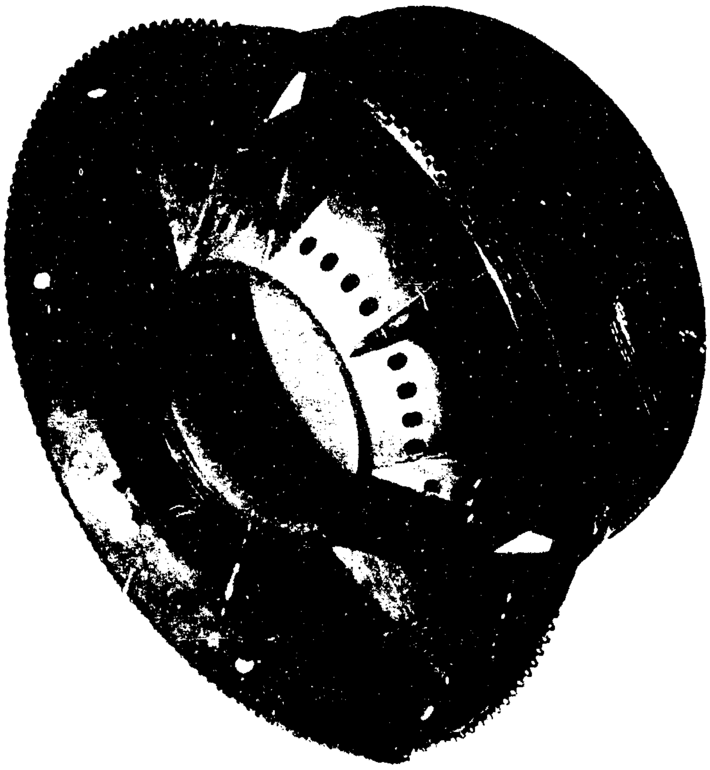

Figure 1. J58 Diffuser Case Complicated Waspaloy Weldment — FE 31136 FI

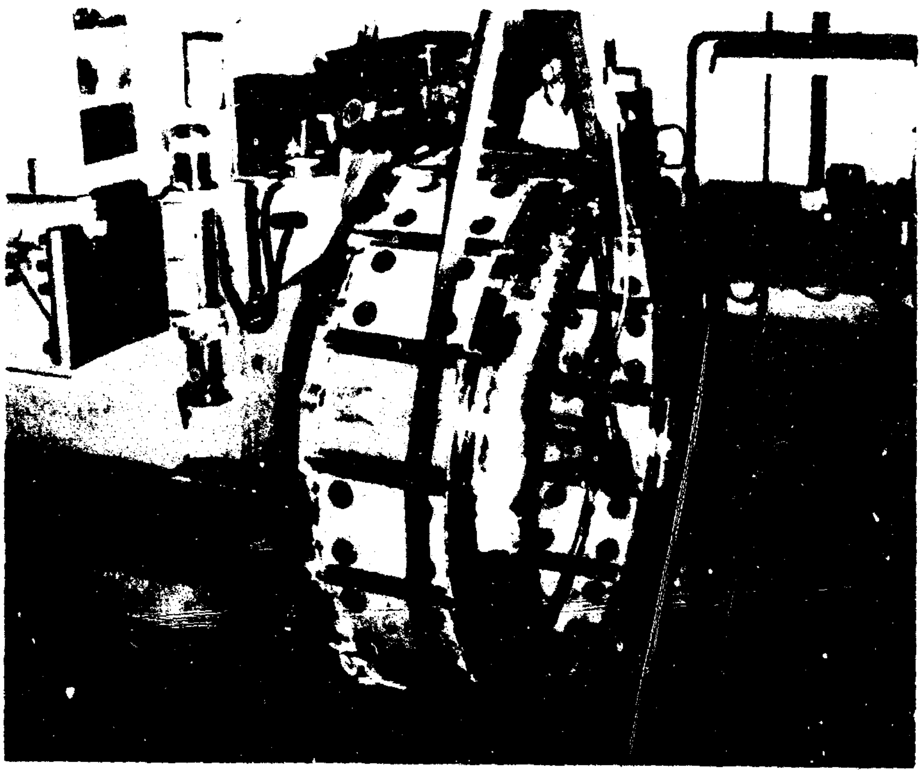

Figure 2. J58 Afterburner Support (Waspaloy Weldment) — FE 59291 FI

Titanium has long been used in P&WA engines. The J58, again, contains titanium assemblies. A titanium vane and case is illustrated in figure 3, while a complex variable inlet guide vane is illustrated by figure 4.

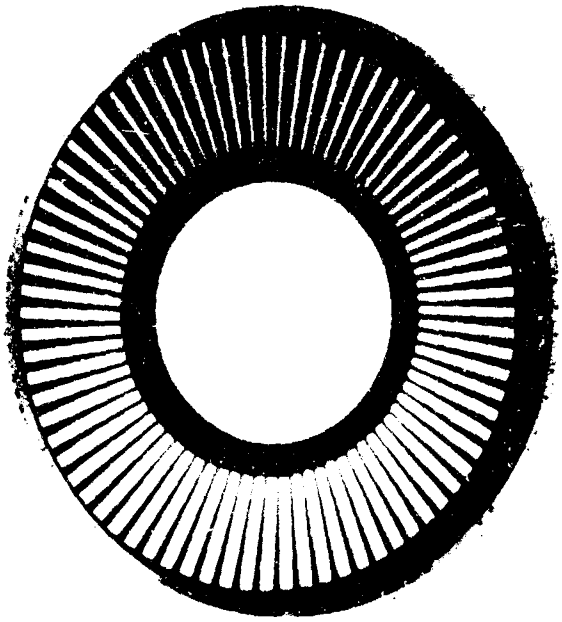

Figure 3. J58 First Compressor Stage Vane Case Titanium Alloys A110-AT and 8AL 1MO-1V   FE 61596 FI

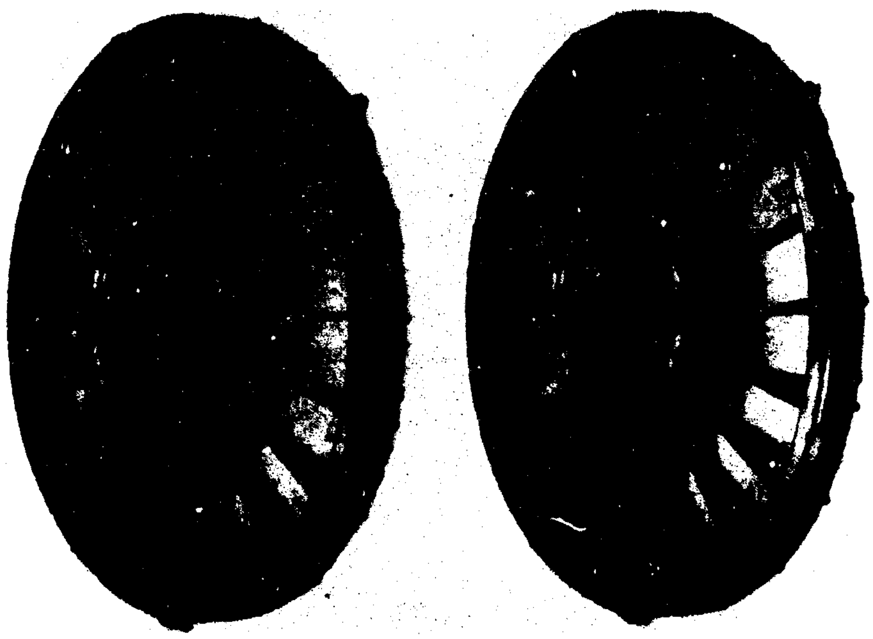

Figure 4. Variable Inlet Guide Vane and Case (Titanium Alloy A110-AT)   FE 46777 FI

TD nickel is of interest because of its good strength at high temperature, good thermal conductivity, and high melting point. Techniques for forming and joining this dispersion-hardened alloy have been in use in the manufacture of J58 burner rings (figure 5), J58 afterburner duct liners (figure 6), and J58 1st-stage turbine nozzle vanes.

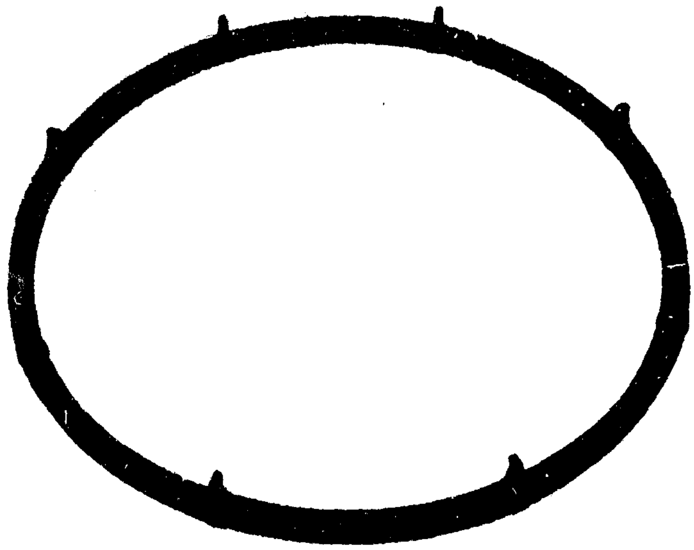

Figure 5. Experimental J58 TD Nickel Gutter for Flameholder — FE 60818 FI

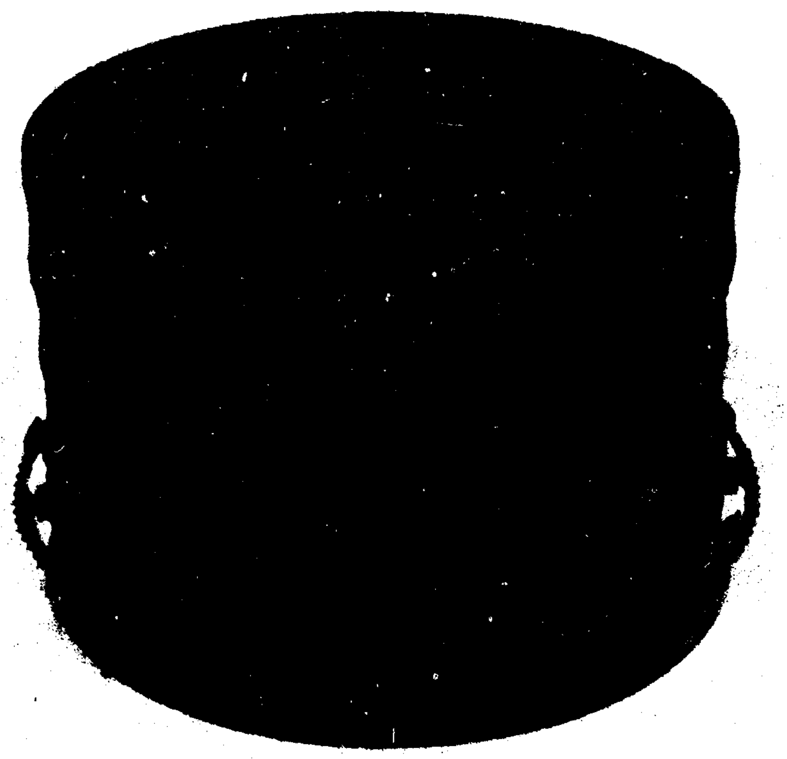

Figure 6. Experimental J58 Nickel Afterburner Duct Liner — FE 49591 FI

In developing and producing commercial and military turbojet engines, P&WA has used 30% of the titanium, 55% of the Waspaloy, and 60% of the TD nickel produced in the United States of America.

The advanced manufacturing development, process improvement during experimental manufacturing, process improvement during production, and the process control system in use at Florida and Connecticut operations of P&WA are described below.

1. Advanced Manufacturing Development

P&WA combines current processes with new processes as they are made available through the advanced manufacturing development groups at Connecticut Operations and FRDC. One such group, Fabrication Research at FRDC, illustrates the duties and functions of these advanced groups.

This group becomes familiar with the new processes, develops new processes, and adapts these new processes to use in experimental and production manufacturing. This group also develops and issues standard manufacturing procedures, helps in the solution of current manufacturing problems, conducts manufacturing research on advanced design concepts, and disseminates information on new processes to experimental and production manufacturing. Fabrication Research is staffed with graduate engineers having a wide variety of education interests, skills, and experience related to manufacturing. These include metallurgy, welding, brazing, machining, forming, electroplating, and heat treating experiences that average 18 years per man. Educational backgrounds include degrees in Mechanical Engineering, Metallurgical Engineering, and Chemistry.

Other groups at Connecticut Operations doing similar or even more extensive manufacturing development are Weld Development Laboratory, Materials Development Laboratory, Production Engineering Chemical and Metallurgical Processing Group, Experimental Planning, The Advanced Materials Research and Development Laboratory, and the Equipment Design and Standardization group. Cross flow of information is obtained by regularly scheduled meetings between the FRDC and Hartford Groups. Manufacturing advances from these groups are applied to the experimental manufacturing and production manufacturing of the SST.

2. Process Improvement During Experimental Manufacturing

Process improvement continues during experimental manufacturing to eliminate those design-associated, material-oriented, tooling-dependent, or processing-connected problems. During experimental manufacturing phases, the design may change as a result of information gained during testing, or, because of changing requirements, a new or improved material may become available, or an improved process may be ready for shop tryout. To assist in accomplishing the dual objective of incorporating these changes and still produce high-quality experimental parts, a system of manufacturing research and development functions at FRDC. Work in this system is initiated through a request from the Program Manager or project engineering personnel closely associated with the requirement. The Fabrication Research Group then develops a solution to the problem, working separately from the groups occupied with the manufacture of parts. By this method, new ideas are generated for new approaches to a specific requirement or elimination of trouble areas.

Testing is conducted to investigate design changes and material acceptability for future consideration from a manufacturing viewpoint. Testing is also conducted to improve tooling and processing techniques. In this system, those problems requiring several weeks for a solution are delegated to the Fabrication Research Group. Problems where the solution is anticipated in a few days are assigned to the Planning Group. All work is documented by a formal report complete with sketches, photographs, charts, and graphs. Figure 7 illustrates the format for these reports.

This well-developed system serves not only to assist in producing high-quality experimental parts, but also to prevent repetition of errors in processing when a prototype part that is producible by a known and acceptable process is released by experimental manufacturing to the Production Department as written process sheets.

Subject: Research and Development Procedure

Report Format

Report No.

PRATT & WHITNEY AIRCRAFT

TO: ______________________ DATE: __________

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SUBJECT: ______________________

TITLE: ______________________

OBJECTIVE: ______________________

SUMMARY: ______________________

CONCLUSIONS: ______________________

PROCEDURE: ______________________

RESULTS: ______________________

DISCUSSION: ______________________

RECOMMENDATIONS: ______________________

DATA: ______________________

ATTACHMENTS: ______________________

INDEXING: ______________________

Written by: __________

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Figure 7. Report Format for Manufacturing Research and Development Work at FRDC

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3. Process Improvement During Production

P&WA continues to improve processing during high-volume production. Several development groups constantly work in their own specialized lines, seeking better methods, more economical systems, and better machines for production.

Included in these are:

1. Value Engineering
2. Weld Development Group
3. Equipment Design and Standardization Group
4. Production Engineering Chemical Processing Group
5. Methods Development Groups

4. Process Control System

The Engineering Department formulates process specifications and designates "Source Approved Vendors" where applicable. Process Control starts with these engineering documents and proceeds in the selection of processes described by Pratt & Whitney Aircraft specification or aerospace material specification (AMS).

An AMS is initiated and controlled through the Society of Automotive Engineers and sets forth certain standards on materials and processes in common usage in the aerospace industry.

A PWA specification is designed to control materials and processes not covered by an AMS, or to place more rigid control on a material or process that is covered by an AMS. These specifications are initiated and controlled by engineering groups at East Hartford and at FRDC by approval of the Project Engineer.

After the engineering drawing is complete and appropriate AMS or PWA specifications are referenced, the process planner or manufacturing engineer must select and specify manufacturing procedures either by pilot lot, process specification, operation sheets, or a combination thereof, to provide an overall system of process control for parts and assemblies. These controls are described in the next four paragraphs.

a. Pilot Lots

Tests to improve manufacture, assembly, or performance of raw material, parts and/or engines may be made by processing segregated lots of raw materials or parts in P&WA plants or vendor plants. Such segregated lots are known as "pilot lots." Pilot lots may be initiated by the Engineering, Manufacturing, or Purchasing Departments. Pilot lots initiated by Manufacturing or Purchasing must be approved by the Project Engineer.

Development pilot lots are controlled lots whose material, parts, or processing differ from existing Engineering Department requirements. These also must be approved by the Project Engineer. They are initiated for the following reasons:

1. To determine effect on performance or durability
2. To determine if production is facilitated
3. To determine the acceptability of material from a new engineering designated source (see Section II)
4. To provide data and engineering information.

b. Processing Specifications

Processing specifications are formulated and controlled by the Engineering Department and approved by the Project Engineer. To ensure that processing conforms to the requirements of these documents, the Production Engineering Department formulates and controls Process Material Specifications and Shop Process Operation Procedures. This system of shop control includes PMC's POP's, PS's, and bulletins; the functions of these documents are as follows:

1. Process Material Control (PMD) is a specification approved by the Chief Production Engineer or his designate for procurement control and quality control as follows:
   a. To assure the user of satisfactory processing material
   b. To supplement AMS or PWA specifications when necessary to obtain satisfactory results during processing.
2. Process Operation Procedure (POP) is step-by-step procedural instruction to control a shop process and, therefore, the quality of the manufactured product, and is approved by the Chief Production Engineer and the Chief Materials Engineer or their designates.

3. Process Solution (PS) is a specification for quality control of chemical solutions and mixtures used during processing, and is approved by the Chief Production Engineer and the Chief Materials Engineer or their designates.
4. A bulletin is an interim amendment to a POP, or a POP in the process of refinement. These also require approval of the Chief Production Engineer and the Chief Materials Engineer or their designates.

c. Operation Sheets

Each part or subassembly is produced to a set of instructions issued to the Experimental or Production Departments, detailing the step-by-step sequence of operations and the equipment to be used in producing the part or subassembly. These instructions are known as the Operation Sheets and are written by manufacturing engineers or planners to ensure compliance to the requirements of the engineering drawings. These documents are approved by the Chief Production Engineer or his designate.

Included as entries in the Operation Sheets are instructions to use Bulletins, POP's, P&WA specifications, or AMS where these are applicable. The specifications referred to provide additional standardized control of processes known to require precise control and those processes of a chemical or metallurgical nature. Examples of these are PWA specifications for electrochemical and electrodischarge machine processes, PWA specification for gold nickel brazing, POP's for the heat treatment of Waspaloy, bulletins for the heat treatment of large Inconel 718 assemblies, and POP's for electroplating of metals.

d. Control System

The control system described, along with the engineering drawing, AMS, and PWA specifications, functions to provide an overall system of process control for parts and assemblies. The engineering drawing and its reference to AMS and PWA specifications set forth the requirements to be met for the part.

Materials and solutions are needed in the manufacturing process. These are purchased and controlled through AMS or PWA specifications whenever they exist. In the absence of specifications of this type, processing materials are purchased and controlled by PMC's and PS's, whichever are applicable. A step-by-step sequence of manufacturing operations is planned for the experimental or production departments to follow. These are the operation sheets. These sheets specify standard POP's and amendments (bulletins).

The POP's, bulletins, and operation sheets are the manufacturing process controls that satisfy the requirements of the engineering drawing and the AMS or PWA specifications.

E. CONTROLLED PROCESSES BY ALLOYS

1. Titanium Alloys

a. Introduction

Control of processing of titanium is accomplished by use of POP's for resistance and fusion welding, for heat treatment, and for cleaning; operation sheets for cold forming, hot forming, and machining; PWA specifications for grinding; and PMC's for solvents and argon. Details of the operation and process controls provided are described in the following.

b. Resistance Welding

Preparation for resistance welding of titanium alloys is done by wiping the mating surfaces with a clean cloth dampened with clean solvent such as acetone or xylene, and having the operator wear clean white gloves to prevent fingerprint contamination.

c. Fusion Welding

Preparation for fusion welding is done by wiping and polishing the mating surfaces with a clean cloth dampened with clean solvent such as acetone or xylene. Welding is done in an atmosphere chamber containing 99.99% argon after a satisfactory test sample has been welded. Argon is purchased to a PMC which specifies a maximum of 100 parts per million of all impurities.

d. Cold Forming

Cold forming is done on titanium only if the bend radius is four times metal thickness or larger.

e. Hot Forming Using Titanium Blank as Resistor

In this system of forming, the titanium blank is placed between the two halves of the forming die in such a manner that it does not touch either die section. The die halves are at room temperature. The blank is connected to an electric power source through water cooled electrodes. When power is applied, the blank heats up uniformly, and, when it is at the proper temperature as determined by an infrared meter, the press is actuated to close the die. Just before the die section touches the hot blank, a microswitch is actuated to turn off the power. The spring system that holds the blank clear of the die during heating retracts under the forming pressure to allow the blank to contact the die surfaces.

Temperature varies with the alloy being formed. The aluminum-tin-titanium alloy AMS 4910 (A-110AT) is formed when the blank reaches 1450°F. The PWA 1202 (Ti-8Al-1Mo-1V) alloy is formed when the blank reaches 1650°F. These temperatures are specified by the operation sheet.

f. Furnace Hot Forming

Details are formed by heating both the die and blank in an electric furnace at a temperature specified by the operation sheet. Both tool and part are then removed from the furnace and immediately formed in a hydraulic press. Nickel-base die materials are used. Forming temperatures vary with the alloy being formed. AMS 4910 (A-110AT) is formed at 1250°F and PWA 1202 (Ti-8Al-1Mo-1V) at 1450°F in this forming process.

g. Hot Die Forming

Dies are heated by means of metal strip resistors inserted in drilled holes or by gas flame. Embedded wire resistors are utilized to heat ceramic dies. The titanium blank is placed in the heated die and allowed enough time to attain the temperature of the die. It is then formed to the desired shape. Operation sheets specify controls for this process.

h. Heat Treatment

All formed details and welded details or subassemblies are stress-relieved at appropriate time and temperature for the alloy in 99.99% pure argon to provide a bright stress relief. Heat treatment is controlled by POP. Bright stress relief facilitates inspection, prevents metal contamination, and facilitates repair of weld defects. Some details that are to be machined all over and details suitable for descaling are stress relieved in air. Descaling is accomplished with a molten caustic salt process followed by a bright dip in an approved mixed acid bath. This process is specified by POP.

i. Machining and Grinding

On all machining operation of titanium alloys, the rigidity of the cutting tools and holding media are of prime importance; in many instances, such as turning, boring, and milling, stock removal per cut can be more than doubled by using massive clamping or chucking devices. The selection of machine tools by the Process Planning Group fulfills these requirements of rigidity and thus increases machining speed. The machinability rating of titanium is approximately 30% compared to 16% for the high-temperature nickel alloys. Carbide cutters are used for turning and boring for extended tool life. High speed drills, end mills, and milling cutters are generally used with carbide inserts again preferred for longer cutting life. Broaches are made of high-speed steel. On titanium alloys, broaching speed is 12 to 14 feet per minute. A 12-degree face angle and 3-degree backoff angle is used on each broach tooth. Stock removal is 0.0003 inch per cut on roughing and 0.001 inch on finishing for each broach tooth.

In those instances where grinding may be detrimental, the engineering drawing states "Grinding Not Permitted." When grinding titanium is specified, silicon carbide wheels are used with a maximum of 4000 surface feet per minute and a down-feed rate not to exceed 0.0005 inch per pass. During the grinding operation, the work piece is flooded with a heavy duty, high sulphur content grinding oil. This oil is controlled by a PMC.

j. Polishing

Polishing of titanium is closely controlled by operation sheet instructions to the operator and is performed using silicon carbide abrasive cloth and maintaining a minimum amount of pressure to prevent sparking and burning. Butterfly finishing of compressor and turbine rotor holes (PWA 99-2) is used to remove tool marks and to obtain the surface finish specified on the engineering drawing. This operation is performed at 18,000 rpm using an airgun type unit mounted on a drill press to which is attached an abrasive cloth (120-grit aluminum oxide) formed on a brass rod for insertion into the hole. The cutting cycle is 20 to 30 seconds with the spindle moved vertically in and out of the hole at two strokes per second.

k. Cleaning

Titanium alloys are kept in a clean and noncontaminated surface condition during welding and heat treatment. White gloves are used when the parts are handled. Dirt is removed by wiping with approved solvents rather than vapor degreasing whenever wiping techniques apply. Solvents and fingerprint suppressors are used judiciously together to rid the part of grease and fingerprint oils and chloride-containing salts prior to heat treatment. A low temperature bake assures removal of the solvent before thermal treatment. Welding, including tack welding, is performed in an enclosed chamber purged with high purity argon. Fluorescent penetrant residues are removed by alkali degreasers, after which the part is thoroughly rinsed in tap water to remove alkali and in deionized water to remove chlorides.

2. Age-Hardenable Nickel-Base Alloys

a. Introduction

The controls on age-hardenable nickel-base alloys are similar to the controls on titanium. PWA 100 sets forth conditions for heat treating of complicated welded assemblies, because these alloys are subject to weld-associated cracking during heat treatment. POP's specify the actual step-by-step operations to meet the requirements of PWA 100. Machining coolants and solvents are procured in accordance with a PMC specification. Cleaning is performed to POP's. Welding is performed in accordance with POP's that reflect PWA 16, the specification for fusion welding. Machining and choice of machine tools and tooling is controlled by the planner who prepares the operation sheets.

b. Cleaning

Nickel-base alloys are cleaned before welding, heat treatment, and after fluorescent penetrant inspection. Preweld cleaning utilizes the conventional solvent degreaser and alkali degreasers to remove grease, oil, and shop dirt, if there are no areas in the part for solvent or salt entrapment. Assemblies that can be adequately flushed are degreased flushed, dried, and abraded at the mating surfaces. The final clean is a wipe with a clean cloth dampened with high purity solvent. Preheat treat cleaning is similar to preweld cleaning only if there has been a fluorescent penetrant inspection. In the absence of such inspection, all exposed surfaces are solvent wiped to remove dirt, fingerprints, and tape residues before the part or assembly is sealed in a retort for heat treatment. Post-fluorescent penetrant cleaning is accomplished with alkali cleaners and a thorough flushing and drying.

c. Welding

Welding of nickel-base alloys is done in accordance with PWA 16. Whenever practicable, semiautomatic machine welding is used. All welding fixtures are designed to provide argon backup gas to the penetration side of the joint and to maintain part configuration with minimum restraint. In many instances, backup grooves or backup cups cannot be utilized because of the inaccessibility of the backside of the weld. Backup gas is then provided by full or partial bagging technique, depending on size and configuration of the part. These backing techniques are necessary for clean, oxide-free welds.

d. Heat Treating

The critical portions of the post-weld heat treating centers primarily in the heating rates and cooling rates. Fast rates are desirable. These, of course, must be modified within the distortion limits that can be tolerated by the part being heat treated. In the heat treatment of nickel-base alloys, uniformity of heating is controlled through selective heat shielding and a preheat of the assemblies to a uniform temperature of 950^{o} to 1000^{o}F just prior to loading into a high heat furnace. Atmospheres are argon or hydrogen, and dew point level is controlled to minimize scaling. This process is described in a FOP which reflects the requirements of PWA 100. Temperature, heating rates, cooling rates, preheat temperature, atmospheres, and dew points are specified in the POP. Heat treatment cycles on nickel-base alloys are kept to a minimum to avoid overexposure to the weld crack inducing environment. Stress relieving cycles to facilitate manufacturing are judiciously used. Material properties for the final assembly are provided by the appropriate heat treat cycle before final machining.

e. Machining and Broaching

The rough and finish turning and boring of age hardenable nickel-base alloys has been considerably improved since their introduction, and tool life has increased through the use of carbides on Astroloy, Inconel 718, and Waspaloy. For roughing cuts, the average depth of cut is a minimum of 0.050 inch to a maximum of 0.100 inch with 30 to 40 surface feet per minute. For finish cuts, surface feet per minute averages 40 to 50. Feed per revolution averages 0.008 inch for best results. A positive rake type cutting tool extends cutter life considerably over negative rake type, both for roughing and finishing. A minimum of 0.006 inch depth of cut is essential to prevent work hardening of the surface. A water soluble detergent coolant is used for all turning and boring operations.

For milling operations, conventional milling is preferred over climb milling, except for slotting or keyway type cuts. Feed rate averages from 0.750 inch to 0.875 inch per minute. Spindle speed is 18 to 22 revolutions per minute with a chip load per tooth of 0.002 inch to 0.003 inch. As with turning and boring, a water-soluble detergent coolant is preferred, with the flood-type proving more satisfactory than the mist spray or other types.

Drilling requires power feed to prevent work hardening of the surface. Carbide or cobalt high speed steel drills perform equally well. Water-soluble detergent, flood-type coolant is used for drilling. Mist spray is used in some applications where flooding cannot be used.

Broaching is performed using high speed steel for increased cutter life. Normally on roughing, 8 to 10 feet per minute with a 0.003 inch per tooth chip load is used. An 18-degree face angle with 2-degree backoff angle proves satisfactory. For finish cuts, all normal conditions for roughing are used except 0.001 inch per tooth chip load. A sulfur based flood type coolant is used.

3. Solution-Hardening Alloys

a. Introduction

Control on solution-hardening alloys is similar to age hardening nickel alloy control, except that PWA 100 does not apply because these alloys are not subject to weld associated cracking on heat treating. This series of alloys responds best to manufacturing methods when the heat treating cycles are controlled to maintain a fine grain size. This is especially true in the fusion welding processes where heat affected zone cracking is associated with grain boundaries.

b. Heat Treatment

Stress relieving temperature is selected to be adequate to provide 100% stress relief from hardening either by forming or machining and to assure no grain size enlargement. POP's control these heat treating processes.

c. Welding

Welding control has been initiated for the incoming material by a simple weldability test that predicts the probable porosity or crack sensitivity of weldments. Such a test is above the specification requirements and is part of the purchase agreement. In manufacturing, the greatest emphasis is placed on gas purity, part cleanliness, and fit-up to make quality welds.

d. Machining

Machining on this group of alloys is characterized by low cutting speeds and ample coolant flow. Better surface finishes are obtained by increasing the speed and decreasing the feed.

4. Dispersion-Hardening Alloys

a. Introduction

This valuable alloy group includes thoria dispersed nickel and thoria dispersed nickel chromium. Handling practices for this radiation bearing material are in accordance with regulations set up by AEC, State of Florida, and FRDC Health and Safety Department. These practices are used in forming, joining, coating, machining, grinding and grit blasting operations on TD Nickel to protect the operating personnel. Process control on these alloys is applied through Bulletins and Operation Sheets.

b. Forming

These alloys are easily formed by normal methods, but in severe forming (such as 180-degree bends that would be used in airfoil sections), routine polishing of the areas to be bent permit crack free sections to be made. Forming is controlled through Operation Sheets and close follow-up by the advanced manufacturing groups.

c. Joining

Thoria dispersed alloys are not weldable by current practices. Standard welding processes such as fusion, resistance or electron beam, results in thoria agglomeration and properties similar to pure nickel rather than PWA 1035 (TD Nickel). To avoid this property degradation, joining by brazing, diffusion bonding, rivetting, or interfacial resistance welding is used.

(1) Brazing

Vacuum or hydrogen brazing with the usual practice of cleanliness and braze fit-up result in good brazes with gold, copper, or nickel alloys. Braze alloy composition is the important control item and is specified in the PWA or AMS specification for the braze alloy. Braze process control is established by POP's that specify cleanliness, atmosphere, braze temperature and time, and fit-up.

(2) Diffusion Bonding

Diffusion bonding is the joining of two pieces of metal under heat and pressure. Neither piece of metal melts and a metallurgical bond is produced by internal diffusion of the two pieces across the interface. Diffusion bonding of PWA-1035 (TD Nickel) is quite readily accomplished over a wide variety of conditions of temperature, time, and pressure. Bonds have been demonstrated to be as strong as the parent metal. Cleanliness of mating surfaces is necessary for consistently good bonds.

(3) Interfacial Resistance Welding

Interfacial resistance welding is closely related to resistance brazing in that the temperature used within the PWA-1035 (TD Nickel) alloy is held to a minimum to prevent thoria agglomeration. A high resistance nickel alloy material shim with a melting point lower than that of nickel is employed to provide the necessary resistance at the interface to cause the shim to melt and join the pieces together. Barrier shims are provided at the electrode sides to prevent the electrodes from sticking to the PWA-1035 (TD Nickel). Welds of this nature have no thoria agglomeration.

(4) Explosive Welding

This technique is limited in that all joints do not lend themselves to explosive welding. Those designs that do are readily joined by this method using the proper standoff angles and distances.

d. Coatings

A PCP which implements the P&WA coating process specification is used. This alloy can currently be protected with a tungsten aluminum plasma coating or a chromium-aluminum pack coating (see Section III, Coatings and Description of Coating Processes, in this report).

e. Machining

Machining by conventional systems and with Electrical Discharge Machining are suitable for these alloys.

C. ILLUSTRATIONS OF CONTROLLED MANUFACTURING PROCESSES (LISTED BY PROCESS)

1. Gold-Nickel Brazing - Shop Control

Controls for gold-nickel brazing are established by P&WA specification. PWA 19 specifies the brazing process and PWA 698 specifies the brazing alloy. Shop brazing processes originated for general or specific requirements are released in the form of a POP. The procedure is supplemented by Operation Sheets originated by Process Planning. The POP and Operation Sheets establish control for the following items:

1. Surface preparation for basis metal
2. Specification for brazing alloy
3. Joint gap clearance for mating details
4. Cleaning procedures prior to brazing
5. Assembly of details to be brazed
6. Methods of heating
7. Atmosphere in which brazing will be accomplished
8. Brazing temperature
9. Time to reach brazing temperature
10. Time to hold at brazing temperature

11. Time to cool after brazing
12. Cleaning after brazing when necessary
13. Examinations for braze quality
14. Permissible repairs if and when necessary

Quality Control Department inspection personnel are assigned to the various plant areas. One of their functions is to observe and verify conformance to all gold-nickel brazing specifications and drawing requirements and to inspect completed braze joints.

2. Gold Nickel Brazing - Vendor Control

Vendor control of gold-nickel brazing is established under the Source Approval System, see Volume IV, Report F, Section III.

3. Induction Brazing

The brazing processes using induction heating sources are widely used by P&WA for development and production operations. Motor generators and radio frequency oscillators are used to provide high frequency ranges from 10 to 450 kilocycles. Power outputs range from seven and one-half kilowatts to one-hundred kilowatts with several in-plant portable power units and others over-the-road portable. Coil connectors and conductors are designed and developed at both Florida and Connecticut operations with the capability of making brazes up to sixty feet from the power source. Control parameters have been well established by research and development work that control braze fit-up, plating of certain precipitation hardened alloys, joint preparation, machine settings, braze alloy, preplacement of filler alloy, brazing temperature and time. These controls are reflected in PWA and AMS specifications for material and processes. These are further controlled and refined in internal standardized POP's, PMC's and PS's. All operators are trained and certified to POP's written by Fabrication Research at FRDC or Weld Development Laboratory at Connecticut operations.

P&WA has done extensive work in developing a wide capability for brazing without flux by the use of controlled atmospheres around the joint. For certain work where a very precise time and temperature control is required, equipment has been developed to perform the task by sensing temperature and controlling output through the use of fast-acting saturable core reactors. In addition, a chart record of the time and temperature is maintained.

4. Integral Element Brazing

Integral element brazing is a brazing process using resistance to electrical current as the heating method. It is unique to P&WA for brazing tubing standoff assemblies and differs from resistance brazing inasmuch as the current flows through the tube detail and not through the braze joint. The tube detail acts as a resistor and is heated as current passes through. The heat from the tube travels to the braze joint by conduction to the braze alloy and standoff detail (see figure 8). Controls are established by POP's, which details the process and describes the machine qualification procedure. All brazing is done in a high purity argon atmosphere. The Quality Control Department has continuous surveillance over the operation and resulting braze joints.

Figure 8. Integral Element Brazing Set-Up for Brazing Standoff Collars on Plumbing FE 61597 FI

5. Metal Gathering

The technique of metal gathering of tube ends to make integral tube fittings is a P&WA development to eliminate brazing or welding of engine plumbing fittings. The operation requires the use of a specially equipped machine tool that has the capability to control heat input and plastic flow at a tube position and ram movement to effect the increase in the cross-section area and mass (figure 9).

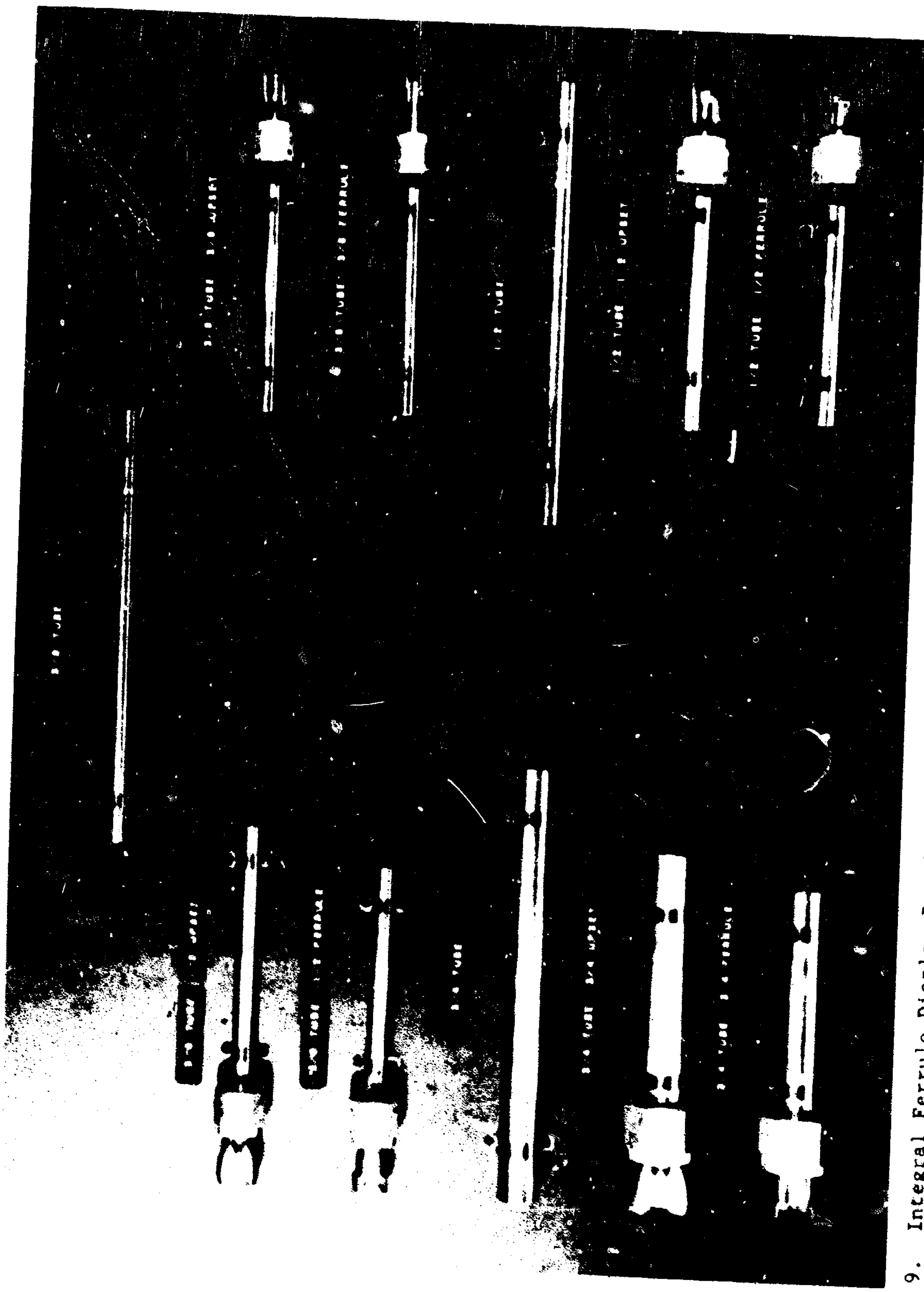

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Figure 9. Integral Ferrule Display Board Showing Metal Gathered Tube as First Step in Producing Brazeless Plumbing

The machine operation is one of precision in all control parameters. This precision is refined to the extent that tube walls of 0.020 inch are easily gathered in all common sizes used in engine construction. Stainless steels are the common alloys used in this process. Other alloys capable of application to this process are titanium and the precipitation hardening alloys. Production equipment has been in use for several years yielding consistently high quality in the manufactured parts. Detail controls that are applied through a POP consist of qualifying a schedule for each tube alloy and configuration, and a verifying control for each production run. The qualifying schedule includes laboratory evaluation of physical properties and micro and macro examination of the gathered end.

6. Explosive Forming and Welding

Explosive forming techniques are widely applied on development and production parts. Explosive welding is used in manufacture of experimental dispersion hardened alloy assemblies. Existing capability provides for forming of sheet alloys in thicknesses from 0.004 inch to 0.250 inch and welding thicknesses from 0.002 to 1 inch. A wide variety of ferrous, nonferrous, dispersion hardened and composite materials can be formed by explosive working.

Size of parts worked is limited by tooling. Five vacuum stations, two open stations, and one remote station are available. Die materials in daily use are plastic faced steel, zinc alloy, and low alloy steel. They are selected in accordance with the number of parts to be made.

Control of the operations is established by a specialized group licensed by the State of Florida and approved by the P&WA Safety Department. This group selects explosive material (sheet, cord, or moldable) from the several that are available, calculating and designing the charge size and selecting the optimum system to suit the material and tooling. These data are furnished to shop operations in the form of detail Operation Sheets for each part.

7. Electron Beam Welding

Electron beam welding controls are established by PWA Specification, POP's and by Drawing Requirements supplemented by Operation Sheets. PWA 16 specifies welding controls in detail, such as preparation, filler material, joint design, penetration and soundness. POP establishes qualification procedures for qualifying operators. Operators must be proficient in the following.

1. Filament replacement procedures
2. Electron gun alignment
3. Establishment of welding schedules
4. Welding of test joints of all associated metals and alloys

Quality Control Department has continuous surveillance. P&WA instructors are used for training of qualified operators. Welding schedules are developed and proof of satisfactory weld is established prior to welding a part or assembly. X-ray techniques for non-destructive testing are in use where applicable. Machine maintenance is on a regular schedule basis.

8. Electrochemical Machining

Electrochemical machining consists of metal removal by passing a direct current between the part (anode) and a tool (cathode) through a suitable electrolyte. The process is controlled by PWA 97, which specifies that the surface shall be free from pitting, burning, selective etching, cracking, intergranular attack, and other imperfections after electrochemical machining. This procedure requires that Engineering approve when and on which parts this process may be used. It further specifies the approval of test specimens and the submission of machine description and settings, process controls and inspection methods prior to Engineering approval of the process for a specific machining operation. Further controls on details of the process and electrolytes are covered by POP's and PS's.

After a machine schedule (voltage, amperage, feed rate and electrolyte) has been established, the operator can make only slight modifications (less than 5%) to this schedule, without Engineering approval.

9. Electrodischarge Machining (EDM)

Electrodischarge machining consists of metal removal by discharging electrical energy between the tool and the part. Thousands of sparks per second vaporize minute craters and erode the tool shape into the part leaving a thin remelted furface layer. EDM takes place in the presence of a flowing dielectric fluid. The process is limited by PWA 97 which specifies that the surface shall be free from pitting, burning, cracking, intergranular attack and other imperfections. This procedure requires that Engineering approve when and on which parts this process may be used. Engineering also specifies whether the remelted layer must be removed or whether EDM surface is satisfactory. PWA 97 further specifies the approval of test specimens and the submission of machine description and settings, process controls, and inspection methods prior to approval of the EDM process for a specific machining application.

After a machine schedule (frequency, current, capacitance, gap voltage and polarity) has been established, the operator can make only slight modifications (less than 5%) to this schedule without Engineering approval.

10. Hard Facing

Hard facing is a process by which hard wear-resistant alloys are applied to the surface of softer metals, thereby prolonging their service life. This process is controlled by P&WA's, POP's and Bulletins which specify:

1. Method of surface preparation
2. Thickness of facing
3. Composition of facing alloy
4. Metallurgical condition of the alloy prior to facing

Other hard facing on P&WA parts is being done by proprietary processes at Source Approved vendors.

11. Surface Coatings

a. Pack Coatings

The use of surface pack coatings by P&WA for high temperature oxidation and abrasion resistance has been very extensive, see Section III. Some of these coatings are vendor applied and others are in-plant applied. The materials and process are controlled by P&WA Specification with further shop operation control, as described in Section I A4. The following items are controlled: preparation of material, packaging of parts, atmosphere purge, sealing of retorts, and the heating cycle to affect the desired diffusion.

b. Spray Coatings

Surface spray coatings are controlled as described in Section III, and are in accordance with the Engineering Drawing requirements. PMC and PS Specifications control the specific materials and combination of mixed materials to be used. POP's and Bulletins detail the process and also call out Inspection and Checking Operations for Quality Control. POP's and Bulletins are supplemented by Operation Sheets. Non-destructive testing methods have been developed and are in use for checking coating thickness and uniformity.

c. Electroplating

Electroplating consists of depositing a metallic coating on a conducting surface (cathode) by means of a direct current passing through an electrolytic bath containing ions of the deposited metal. The process control system specifies the following:

1. Thickness of deposit
2. Cleanliness of the part prior to deposition of the coating
3. Type of plating bath (sulfate, chloride, or cyanide)
4. Temperature of bath
5. Current density

12. Vane and Blade Coating Process

Specially designed coatings, to protect vanes and blades from oxidation and erosion are deposited by spray and pack processes. Each of the processes is controlled by PWA Specifications which specify thicknesses, diffusion temperatures and process materials. These coatings require proper surface preparation and cleanliness of the part for a good bond between the part and coating. After surface preparation and cleaning, special controls such as handling of parts with clean gloves, drying with dry nitrogen, and sealing them in clean plastic bags assures that the part will not be contaminated between cleaning and coating.

POP's control the detail processes so that the quality of coatings is not dependent on operator skill. Thicknesses are further controlled by the addition of metallographic samples with each group of parts and the careful weighing of parts before and after coating to determine coating thickness of the actual parts.

Solutions have been developed to remove these coatings without damage to the basis metals. Coatings may be removed at overhaul for inspection or other reasons.

Re-coating of these parts is a standard procedure which is controlled by the same stringent measure used in the original coating procedure.

D. ILLUSTRATION OF CONTROLLED PROCESS BY TYPICAL MAJOR COMPONENTS

The following paragraphs describe processes for manufacture and controls of three typical major components, a twinned turbine vane and a cast turbine blade in use on the JTF17, utilizing the experience gained in producing similar components for the J58.

The Hastelloy X component, the titanium component, and the Inco 718 component, the TD Nickel vane and the cast turbine blade were chosen to illustrate proficiency in these alloys.

1. 1st-Stage JTF17 Turbine Vane

The 1st-stage turbine vane is fabricated in segments of two PWA 1035 (TD Nickel) airfoils and cast-on PWA-658 (IN 100) inner and outer platforms. Figure 15 in Section II illustrates the construction. Airfoils of PWA-1035 are formed in dies. The developed sheet metal blank is placed in the die with the roll direction perpendicular to the direction of bending. This die forms the blank into a mild butterfly form and produces an expanded airfoil section on the outer end. See figure 10 for the shapes after each forming step. The second die is a fold-up type. The mandrel forms and sets the leading edge radius. A final hot form die completes forming of the airfoil with the use of an internal mandrel. The airfoil is then fixtured in a drill jig and all rivet holes and counter sinks are machined. Internal spacers are fitted to the drilled holes to control trailing edge exit slot size. Rivets are installed through the sheet metal and internal spacers and then upset. The trailing edge of the airfoil is belt sanded and polished to Engineering drawing requirements. All grinding and polishing operations on this alloy are performed in a special decontaminant chamber. The airfoil is then trimmed to establish the nozzle flow area. Holes are then drilled through each outer end of the airfoil. These holes serve as anchors when the inner and outer platforms are cast on.

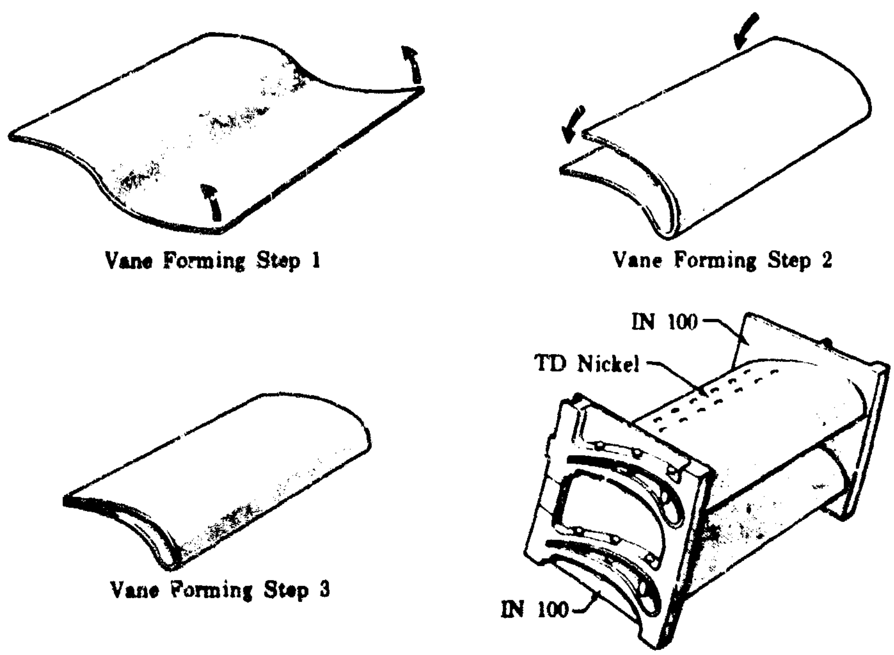

Figure 10. 1st-Stage Turbine Vane for JTF17 and the Forming Sequence for TD Nickel — FD 16711 FI

Prior to casting, the airfoils are coated with a special oxidation resistance pack coating (PWA 62). A sand seal retort slightly larger than the vane is filled with a blend of the coating mixture. The part to be coated is placed in this mixture. The sand seal retort is placed in a large welded retort and heated to the optimum temperature to deposit the coating on the vane in a two-step process. Metallographic specimens are placed in each retort to monitor coating thickness and quality.

The vane is then measured to determine if compensation is required to obtain the desired class or nozzle flow. To prevent contamination during machining, the vane cavity is pressure filled with hot wax, which is allowed to solidify. The vane is then cast into a shuttle using a fusible alloy matrix. A final check to ensure the vane location in the shuttle is made, and the part is then machined. After machining, the vane is decast from the shuttle and classified, inspected, non-destructive tested, and sent to storage.

2. Primary Engine Combustor and the Duct Heater Combustor for JTF17

The primary engine combustor and duct heater combustor are of a modular design which consists of a segmented inner liner assembly and a segmented outer liner assembly that are attached to a segmented annular shaped combustor face. Sheet metal scoops are butt welded to weld stand-ups formed in the inner and outer liner segments.

a. Handling

This assembly is made of AMS 5536 (Hastelloy X). See figure 11. Prior to final fit-up for welding, all detail parts are cleaned approximately one-half inch on both sides of areas to be welded, by hand or power polishing with silicon carbide grit paper. Parts are welded after abrasive residues are removed by wiping the areas with a clean cloth dampened with solvent. After EDM of turning vane slots and just prior to brazing vanes in place, all detail parts are cleaned by immersion in a molten salt bath followed by an acid cleaning to remove discoloration formed during welding. All cleaned parts are protected from contamination by wrapping in clean kraft paper and placing in proper containers for transporting to next operation.

b. Welding

Welding of sub-assemblies and complete assemblies is accomplished whenever possible with the parts enclosed in a portable type welding chamber using a high purity argon gas atmosphere. When parts are welded outside of the chamber, the backside of all welds are enclosed, using plastic sheeting and pressure sensitive tape. The enclosed area is purged with high purity argon gas.

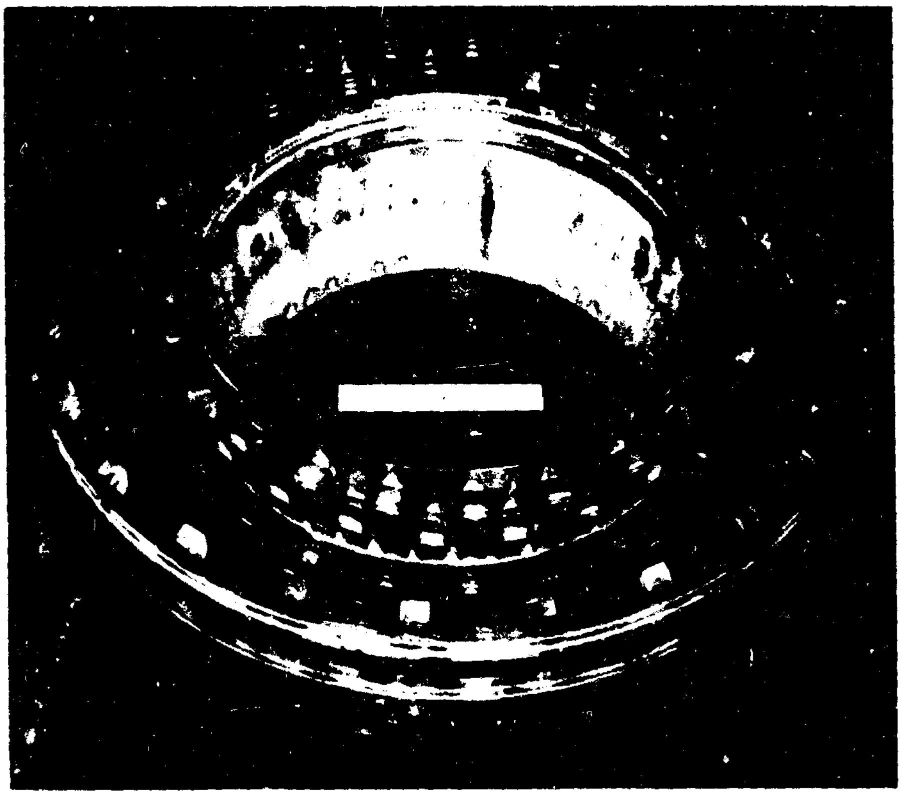

Figure 11. JTF17 Engine Primary Combustor (Hastelloy X) FE 60188 FI

c. Brazing

The turning vanes and air deflectors are brazed into the scoops at 2100°F ± 25°F in a controlled high purity hydrogen atmosphere using a nickel-chrome-silicon alloy. This alloy exhibits the ability to fill wide gaps (approximately 0.010 inch) and form desirable corner fillets.

d. Machining

All machining of the combustor assembly is completed while the combustor face is in the subassembly stage of fabrication.

e. Inspection

Visual examination and fluorescent penetrant constitute the nondestructive "in process" type of inspection. A final radiographic, fluorescent penetrant and a dimensional inspection completes the quality control requirements for this assembly.

3. Intermediate Case Assembly for JTF17

a. Material

This case is made of AMS 4910 and 4966 (A-110AT Titanium) alloy. See figure 12 for illustration. All details for this assembly are formed with the appropriate system described in I.B.1.

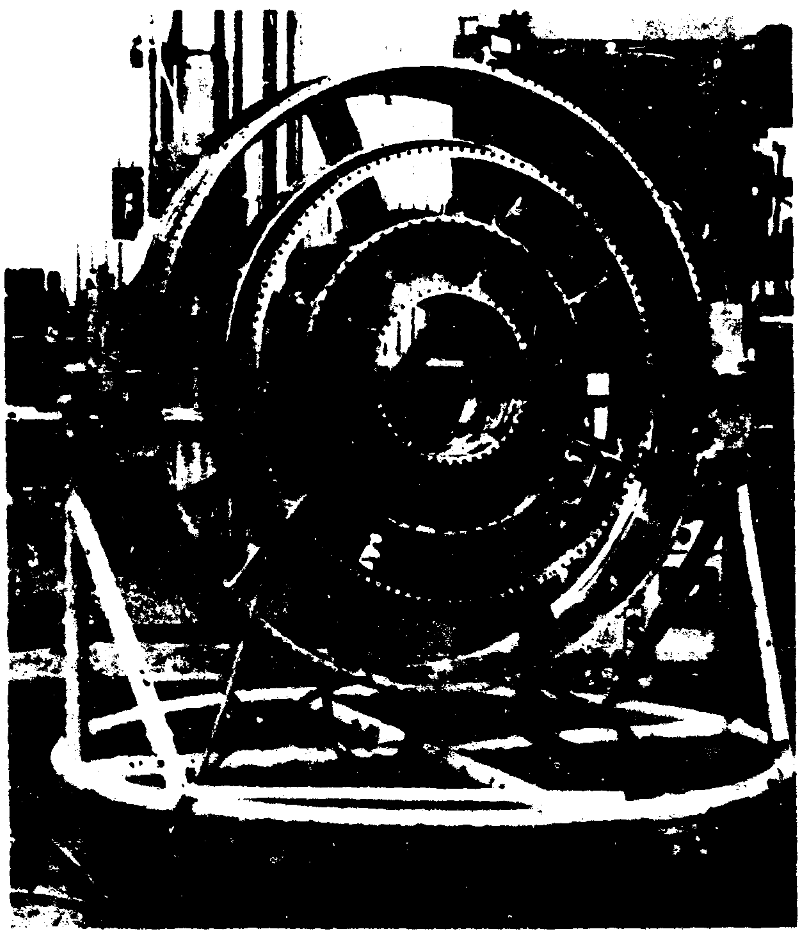

Figure 12. JTF17 Engine Intermediate Diffuser Case (A110-AT) FC 60660 FI

b. Handling

Parts and sub-assemblies are kept in a clean condition by handling them with clean gloves and packaging them in transit in clean plastic bags.

c. Welding

The assembly is fabricated from the smallest diameter out to the largest by locating in register diameters on fixtures, and welding struts to cases. After welding, struts are machined to fit stub struts of next case for proper weld gaps. Welding of struts to cases and all other details are completed while the cases are enclosed in a chamber purged and filled with high purity argon. Test pieces are welded within the chamber prior to welding of the actual part to confirm that the atmosphere is satisfactory.

The struts of the inner case, after mechanical cleaning of the weld area (see Section I.B.1) are assembled and welded with a "J" weld preparation on both case stand up and strut. The strut is tack welded and then welded by a skip tacking and welding sequence on alternating struts to control distortion. The intermediate case is welded onto the inner case in a similar manner after a strut tip machining to control fit-up. Then the outer case is welded onto the intermediate case in a similar manner after a strut tip machining operation to control fit-up.

d. Heat Treat

After welding and inspection are completed, the assembly is thoroughly cleaned and dried, assembled with appropriate fixtures, and instrumented with thermocouples in a sealed retort. Heat treating is done in high purity argon at a controlled purge and dew point.

e. Machining

All machining fixtures are designed to allow the maximum amount of work possible to be completed without changing the part in the fixture or changing fixtures to prevent machining errors.

f. Inspection

Critical inspection by X-ray and fluorescent penetrant is made after welding and after heat treatment. A final dimensional inspection is made after machining. A final cleaning as described in I.B.1. prepares the assembly for use or storage.

4. Diffuser Case JTF17 (Figure 13)

a. Handling

This assembly is made of PWA-1009 and AMS 5596 (Inconel 718). The materials are not subject to injurious contamination by oils and other materials contacted during ordinary shop practices; therefore, no special handling methods are specified. The larger parts, sub-assemblies, and assemblies are transported in special containers.

Figure 13. JTF17 Diffuser Case Inconel 718 FE 61598 FI

b. Assembly and Welding

Parts are fitten on fixtures in preparation for welding. Beveled weld preps are usually hand ground. "J" groove weld preps are machined on details.

Small parts are cleaned by solvent or alkali degreasing. Larger parts and assemblies are cleaned locally by abrasive methods followed by a solvent wipe. After cleaning, parts are reassembled on fixtures and welded by the TIG method, using high purity argon shielding and backing-gas.

PWA-1081 (Inconel 718) filler metal is used in all joints. All joints are inspected with shop fluorescent penetrant and by X-ray before heat treatment. Inside flanges and struts are welded to inner case as a sub-assembly and all welds are inspected by fluorescent penetrant and X-ray. Strut ends are machined to length with 0.015 inch interference fit-up for a "J" type weld to the outer case.

Inner case sub-assembly and outer case are mounted on an assembly fixture to facilitate line up of mating parts. The assembly is held in heavy fixturing until all welds between struts and outer case are completed and all flanges are welded to the outer case. It is removed from fixture, inspected by shop fluorescent penetrant, X-rayed and reworked as necessary.

The assembly is cleaned solution heat treated in a controlled hydrogen atmosphere and inspected by fluorescent penetrant.

The openings for turning vanes are machined to finished size and fitted to a "go" and "no-go" gauge.

The assembly is cleaned, then precipitation heat treated in a hydrogen atmosphere. The entire assembly is X-ray inspected.

c. Machining

The assembly is mounted on a rotary layout table and all machining levels and diameters are checked and scribed. The machining fixture is mounted concentric and level with layout lines. All surfaces on one end are turned to rough finish, then to finished dimensions. The second machining fixture is mounted concentric to and level with the finished end for machining of the opposite end. The assembly and fixture are next moved to the boring mill. All flange faces are machined with single point tools. All bores are machined with special rough and finish form cutters. One bolt hole is drilled in each flange for location of drill fixtures. Bolt holes in all small flanges are located with drill fixtures and drilled with a specialized pneumatic unit. Bolt holes in the large end flanges are located with fixtures and drilled in a radial drill press.

d. Final Assembly

Three tube and fitting sub-assemblies are installed through struts, induction brazed, and pressure tested. The 8th-stage vane and shroud is installed by bolts secured by lockwires.

5. Turbine Blade Manufacture

A typical hollow aircooled blade with a tip shroud containing seals and interlocking notches is processed as follows.

a. Preparation for Machining

The castings are received from a Source Approved Vendor. Parts are mechanically serialized, hardfaced on the notches, cleaned, heat treated in controlled atmosphere, and fluorescent penetrant inspected following heat treat. Serial number is ink stamped on airfoil in area to be covered by fusible alloy. The hollow core is filled with wax to prevent grinding swarf contamination. The blade is placed in a shuttle block, which uses guillotine type tools to place each blade's average airfoil stacking line coincident with shuttle center line, simultaneously making blade root center plane parallel to shuttle side. It is then locked in place by pouring a fusible alloy matrix in the shuttle block.

b. Machining

The blade root and platform sides are finished either on a dual wheel grinder or large surface grinder. This operation and grinding of the notch hardface are performed in accordance with controlled Engineering directives as to stock removal and spark out passes with a specific type grinding wheel to prevent high residual stresses. The remaining root areas are completed to gauges and charts. The radial seal area is finished by grinding diametrically either on a large surface grinder with an oscillating fixture or on a vertical grinder. Operation Sheet instructions on the amount of feed are given, and inspection is done by flush pin gauges and charts. The seal grinding is done prior to notch finishing to allow for any movement of the shroud induced by the metal removal.

The tip shroud conical hole is electrodischarge machined and the notches are finished gound in direct relationship to the root serrations so that root pressure faces and center origin of shroud interlocking notches are on a radius of the engine axis. This eliminates pre-stress of notches not machined from a common origin. Parts are now removed from shuttle, re-serialized, and burrs removed from root. A complete set of parts loaded on the vertical grinder is finished on leading and trailing edge of root and platform and the underside of platform. All edge breaking, radii forming, and blend polishing is now done. The fusible alloy is melted away with steam and the residue is removed by an acid. The blade is vapor blasted and inspected by fluorescent penetrant.

c. Preparation for Coating

A fixture is placed on the root to permit air to be passed through the core to prevent contamination during grit blasting the airfoil to be coated. Plastic bags are used after grit blasting to eliminate contamination prior to coating.

d. Coating

The airfoil is spray coated to a controlled thickness with an aluminum type, oxidation resistant coating. A metal shield is placed over the root during the diffusion cycle to prevent root contamination with coating splatter. The coating and diffusion operations are performed to controls set up by PWA Specifications, POP's and Bulletins.

e. Finishing

The core is again filled with wax prior to finish drilling of the platform dimple, identification, deburring, vapor blasting, and shot peening of the root. The wax is then removed, and the core is thoroughly cleaned. The blade is inspected, marked, and fitted to the disk. The assembly is hot spun to controlled engineering directives. Before the blade is stored, it is dimensionally inspected and chemically checked for alloy type.

f. Inspection

The blade is inspected for defects by fluorescent penetrant and mercury X-ray, and is X-rayed again for mercury removal and dimensionally inspected for conformance to Engineering Drawing.

E. DEVELOPMENT AND APPLICATION OF NEW PROCESSES

Development of new materials, as well as new applications for existing materials, inevitably requires concurrent development of improved processing techniques. As demonstrated by several instances in Section II, the inherent capabilities of a selected material can be optimized for a given application by intensive development of, and close control over, all processing variables. Such development is the joint responsibility of several groups within P&WA, including Materials Development Laboratories, Advanced Materials Research & Development Laboratory, Fabrication Research, Weld Development Laboratory, and Production Engineering. Extensive in-house facilities (see Volume V, Report B) plus P&WA directed development programs at sub-contractor facilities, are available for this effort. In many of the following areas, P&WA has already provided leadership in producing markedly superior engine parts through improved processing. In the remaining areas, we have studies underway to exploit the potential improvements. Improvement in processes for casting, forging and rolling, heat treating, joining and coating will receive major emphasis on Phase III of the SST. Other manufacturing methods with anticipated improvements that will be available during Phase III are tabulated in Item 6 that follows.

1. Casting

In Section II.F., the improvement in properties of a given alloy for Turbine Blade application by successively improving techniques in moving from uncontrolled grainsize to "Grain X" to directionally solidified castings to Monocrystals, is demonstrated. Substantial improvement in hardware reliability by close control over melting and casting variables will be demonstrated in other critical applications, such as Turbine Vanes and Exit Nozzle Guide Vanes.

2. Forging and Rolling

Properties and durability of J58 disks today are significantly higher than they were prior to the development of improved processing techniques. This was accomplished by systematic investigation and application of working techniques, in order to produce a more uniform, stronger part. The basic principles evolved will be applied, with modification, to titanium compressor disks and blades, Waspaloy and Astroloy disks, shafts and hubs, and sheet alloys to be used in the JTF17 engine program. The established process of form rolling will be utilized to produce intricate shapes with desirable mechanical properties in super alloys and titanium alloys. Cost savings are expected by reducing the amount of raw material and machining as a result of improvements in the state of the art that permits form rolling close to the final machined contour.

3. Heat Treating

The development of optimum properties in age-hardening nickel-base alloys, as well as in titanium alloys, is highly dependent on selection of heat treatment cycles. Heat treatment studies made in conjunction with visual and electron microscopy evaluation will continue on materials used in the JTF17.

4. Joining

a. Mechanical Methods

Mechanical methods, such as bolting, are continuously under study. Investigation of stress-relaxation characteristics of high-temperature bolting, using P&WA-developed rigs, has led to solution of engine problems. P&WA has demonstrated that production of optimum bolting is highly dependent on alloy selection, forging and rolling techniques, and heat treatment.

b. Brazing

P&WA will continue development of improved and more economical braze alloys and methods. Brazing of thoria-dispersed nickel is discussed in Section I-D-1. A new technique for brazing tube stand-offs is also mentioned in Section I-C-4. In the interest of economy, a suitable replacement is needed for Gold Nickel. To provide higher temperature service for TD Nickel, improved nickel base braze alloys are needed.

c. Diffusion Bonding

Diffusion bonding offers promise in joining similar or dissimilar metals, and has potential application in the advanced "wafer-type" turbine vanes which P&WA is developing. Wafer type air cooled turbine vanes allow an infinite variety of cooling schemes and is made practical by diffusion bonding the individual wafers together to make an integral vane. Diffusion bonding will be developed to its fullest for use in JTF17 vanes and other applicable parts for similar as well as dissimilar metals.

d. Welding

Electron beam welding has become a production method, and applications are being expanded to major components. A vendor controlled specialized friction welding process called inertia welding is under continuous development for application to P&WA engine hardware at P&WA and sub-contractor facilities.

The mechanism of crack initiation and propagation during and after welding is under intensive study. Heating and cooling rates, degree of restraint, purity of atmospheres, presence of contaminants, and prior history of the parent material are known to influence the soundness of the welded structure.

Improved radiographic techniques which shows smaller defect continue to be of value in contributing to sounder weldments.

5. Coating

This subject is discussed in detail in Section III. All of the following methods have potential applications in the JTF17:

1. Gas Plating (Pack)
2. Electroplating
3. Paint Systems
4. Dipping
5. Cladding
6. Vapor Deposition

6. Other Advanced Manufacturing Methods

The following advanced manufacturing methods are under continuing development at P&WA or sub-contractor facilities:

1. Chemical milling, including new masking methods and side etch inhibitors
2. Use of low temperature salt baths for descaling titanium
3. Deburring by electrochemical methods

4. Deburring by exposure to gaseous chlorine
5. Electrochemical and Electro-discharge machining methods
6. Use of lasers to drill small precision holes
7. Use of adhesives for joining titanium and aluminum components
8. Composite constructions for added strengths and lighter weights
9. Skip turning over and around bosses for high speed metal removal
10. Electron beam hole drilling for small diameter holes
11. Continued development of numerical controlled machining tooling and processes
12. Co-extrusion of alloys to produce an erosion and corrosion resistance surface
13. Cryogenic strengthening of metals
14. Explosive cladding
15. Photo masking for plating
16. Straight and curved small diameter hole drill by electrochemical machining.

SECTION II

ANALYSIS OF MATERIALS SPECIFIED AND PROPOSED

A. INTRODUCTION

There are two unique accomplishments that will contribute to the successful development and production of the JTF17 supersonic transport gas turbine engine. The first is the increasing of time-between-overhauls of the widely used commercial JT3D engine to an unprecedented 8000 hours. The second is the production qualification and successful introduction into service of the J58 continuous supersonic cruise engine. The technology which has made possible these accomplishments is basic to and indispensable for the successful development of the supersonic transport engine.

Pratt & Whitney Aircraft has long been active in the development of alloys and processes necessary for the production of turbo-machinery. In particular, Pratt & Whitney Aircraft has pioneered in the development and production of aircraft engine hardware from titanium alloys and of oxidation resistant coatings for jet engine hot section parts.

With the development of the J58 engine came some of the most challenging metallurgical development problems ever encountered by P&WA. The unprecedented levels of engine operating temperatures-stress-durability combinations for hardware components throughout the engine required the adaptation of nickel base superalloys, which had been developed and used exclusively for turbine blades, large disk forgings, ring forgings, and sheet components. Extensive alloy development, modification, and process development had to be accomplished to meet hardware requirements. In addition to an extensive nickel base alloy development program, titanium technology had to be extended to alloy compressor blades to operate under the most demanding conditions to which titanium blades have ever been subjected. Finally, advanced coating systems had to be developed to increase the life of components by protecting components against severe environmental effects.

The same group of experienced metallurgists who were instrumental in the development of alloys, coatings, and processes for hardware for the J58 program will be responsible for such development for the JTF17 engine. In addition to extensive turbine engine experience, the supervisory personnel of the group have a broad base of applicable industrial experience, some having previously been employed by metal producers and forging sources in responsible positions involving the management of production vacuum melting facilities and the direction of forging development. The success of the metallurgical development associated with the J58 is attributable in large measure to this base of practical, industrial metal working experience combined with extensive turbine engine metallurgical experience.

The entire metallurgical team, composed of the Metallurgy Section of the Florida Research and Development Center and East Hartford Materials Development Laboratories, will be supplemented by the Pratt & Whitney Aircraft Advanced Materials Research and Development Laboratory at North Haven, Conn. This latter laboratory's mission is to perform fundamental research in advancing the state of the art for producing hardware for all P&WA engine projects. It is staffed with highly competent specialists in all disciplines that relate to materials development.

It is important to emphasize that, functionally, the Materials Development Laboratory, FRDC, receives the technical objectives for materials and process development directly from the JTF17 Program Manager. Experience in the J58 engine program has established the necessity of tying the materials organization directly to the engine project organization in order that the metallurgical personnel are thoroughly familiar with the engine and its problems and the program management personnel are fully cognizant of the materials, processes, techniques, and experience available for use in the JTF17 program.

With the background of proved achievement, support of a highly competent Advanced Materials Research Laboratory, and an organization in position that assures the most productive effort, the Materials Development Laboratories of P&WA are well qualified to fulfill the materials and process development so vital to the success of the supersonic transport gas turbine engine.

This section describes the development activity performed by P&WA metallurgical laboratories in bringing the "Specified" materials for the JTF17 engine (Table 1, Section I, Report F) to their present stage of capability. "Specified" materials are those that will be initially designated on engineering drawings at the start of Phase III. Unless otherwise indicated these materials are expected to apply to both the prototype and production design. Obviously, these initial selections must be confirmed by engine test results. These materials were selected on the basis of mechanical property evaluation carried out under the Phase II-C program on candidate materials resulting from previous commercial and advanced high Mach number engine experience. Although it is stated or implied in the discussion of all "Specified" materials it is to be emphasized that in all cases the availability of quality material on a reproducible basis was considered a prime requisite, along with the metallurgical suitability, for the selection of all materials.

In addition to "Specified" materials, advanced metallurgical development on Proposed materials now in progress is also described which has potential for the evolution of new materials and processes for progressive upgrading of the performance of the JTF17 engine.

Specifically, this Section is comprised of sub-sections covering classes of alloys including titanium base, iron base, wrought nickel base, cast nickel base, and cast cobalt base alloys. In the case of each sub-section, discussion is carried out under two headings, viz. Specified Alloys and Proposed Alloys. Under the first of these headings, each alloy "Specified" along with the major components which it is to comprise are listed from table I, Section I, Report F. Following this is a discussion of the alloy substantiating its metallurgical applicability. Under the second heading, i.e. Proposed Alloys, each alloy which offers potential for upgrading the performance of the JTF17 is listed along with a discussion of the metallurgical development and results which substantiate its promise.

In addition to the sub-sections covering Specified and Proposed materials, a sub-section on low cycle fatigue (LCF) as applied to compressor and turbine disks is included. This sub-section is important because of the very critical nature of this property in determining the success of the JTF17 engine. Because of the importance of microstructural control on disk LCF performance, as well as the control of all mechanical properties on disks and other rotating parts, a final sub-section is included on the metallurgical control of major rotating parts.

B. TITANIUM ALLOYS

1. Introduction

The advantage of titanium alloys in aircraft gas turbine engines was first exploited by P&WA metallurgists and engineers for the substantial weight saving offered to compressor hardware. A titanium compressor rotor was engine tested in 1952, and the first production P&WA engines containing titanium were shipped in 1954. For a number of years, P&WA engines utilized over half the United States' output of titanium alloys. This pioneering volume use was largely responsible for the growth of the titanium metals industry in the United States. It is with this background of experience that P&WA incorporates improved titanium alloys in its latest engine design, the JTF17 engine.

2. Specified Alloys

a. PWA-1202

PWA-1202 (Ti-8Al-1Mo-1V) is a near alpha titanium alloy that has been specified for extensive use in the JTF17 engine for the following components:

2nd stage disks	Fan
Aerodynamic brake	Intermediate Case
3rd, 4th, and 5th stage blades	High Compressor
3rd and 4th stage vanes	High Compressor
Duct burner support	Fan Duct
Fan exhaust nozzle support	Duct Burner
Trailing edge flaps	Reverser-Suppressor
Outer rear skin	Reverser-Suppressor
Rear Ring	Reverser-Suppressor
Inner rear skin	Reverser-Suppressor
Clam shell support, inner skin	Reverser-Suppressor
Clam shell support, outer skin	Reverser-Suppressor
Clam shell support, frame work	Reverser-Suppressor
Intermediate ring	Reverser-Suppressor

Front ring	Reverser-Suppressor
Mount ring	Reverser-Suppressor
A-frame	Reverser-Suppressor

(1) Background

The successful use of Ti-8Al-1Mo-1V alloy in two advanced high Mach number engines, first in the J58 turbojet and later in the TF30 turbofan, has led to the selection of the alloy for the proposed JTF17. In the case of both engines, the alloy was selected over the more common Ti-6Al-4V alloy because of its higher temperature strength capability. Figure 1 compares the creep strength of Ti-8Al-1Mo-1V and Ti-6Al-4V on a strength-to-weight basis.

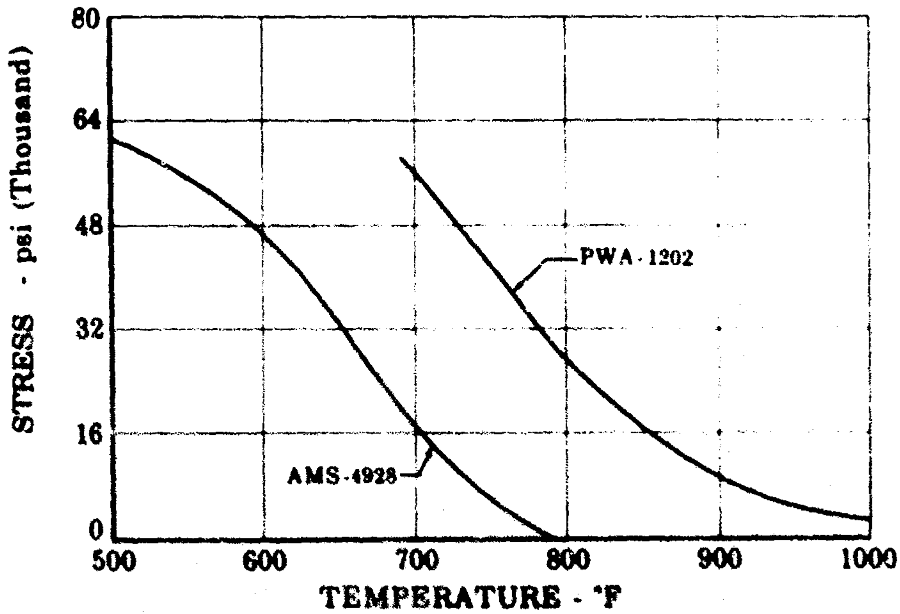

Figure 1. Comparison of 0.1% 6000-Hour Creep Strength of PWA-1202 (Ti-8Al-1MO-1V) and AMS-4928 (Ti-6Al-4V) FD 16572 FII

The alloy is commercially available as sheet, bar, and forgings and has been successfully used both in engines and in the laboratory by P&WA. Based on its successful use in the J58 engine, Ti-8Al-1Mo-1V alloy has become the standard for comparison of new high strength alloys now under development.

(2) Corrosion

All high-strength titanium alloys, such as PWA-1202 (Ti-8Al-1Mo-1V), AMS 4928 (Ti-6Al-4V), and PWA-1203 (Ti-5Al-5Zr-5Sn), are susceptible to some environmental effects.

Titanium alloys are prone to stress corrosion cracking, which generally manifests itself by localized intergranular attack. The first evidence of stress corrosion cracking was associated with premature creep specimen failure which was traced to the effects of fingerprints. In response to this finding, P&WA and titanium vendors initiated a research program, the results of which were published in 1957 (Battelle Memorial Institute report TML #88). Since that time, P&WA has developed testing methods and has continued to define the stress corrosion phenomenon. Current stress corrosion tests are conducted on salt (sodium chloride) coated specimens that are loaded to various stress levels and are exposed at elevated temperatures for time periods up to 1000 hours. After exposure, the specimens are tensile tested at 70°F and the resulting fracture surfaces are examined for any evidence of the characteristic attack. If stress corrosion is detected, the stresses are reduced in subsequent tests until a "safe" stress is obtained at which no cracking occurs. Figure 2 shows typical 150-hour stress corrosion data for PWA-1202 (Ti-8Al-1Mo-1V), AMS 4928 (Ti-6Al-4V), PWA-1203 (Ti-5Al-5Zr-5Sn), and PWA-1205 (IMI 679) titanium alloys. PWA-1202 has been used satisfactorily at metal temperatures up to 900°F in the J58 engine.

The study of stress corrosion by sodium chloride has, by necessity, been limited to laboratory testing. Laboratory testing (figure 2) using substantial quantities of "caked on" sodium chloride is a severe test; therefore, the "no-crack" stress does not directly relate to engine design parameters or actual engine experience. This accelerated test does, however, allow the ranking of various titanium alloys in their resistance to stress corrosion cracking.

A second type of corrosion has been reported wherein precracked titanium alloy specimens have shown low fracture strength in aqueous environments. The first investigators were interested in using Ti-8Al-1Mo-1V alloy in a deep submersible application and found a

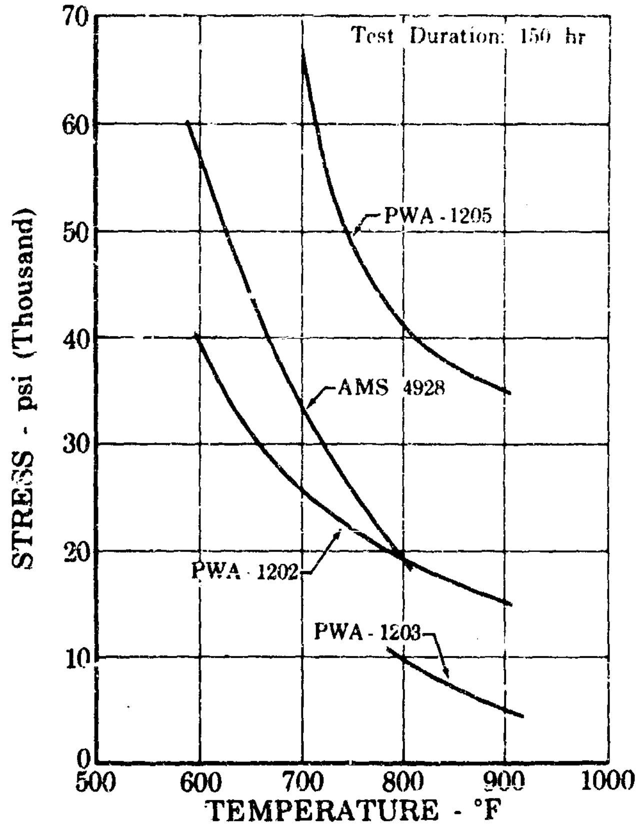

Figure 2. Stress vs Temperature for Accelerated Salt Corrosion of Titanium Alloys — FD 16573 FII

degradation of fracture resistance in sea water; additional examinations found that fresh water would also cause the deleterious effect that is frequently described as aqueous stress-corrosion damage. This phenomenon results in an increased rate of crack propagation when precracked specimens are exposed to aqueous (fresh or salt water) environments and to stresses at the crack tip above a certain threshold value. P&WA tests have been directed solely toward evaluating the implications of this effect on gas turbine components such as vanes, disks, and welded structures. In examining fatigue-limited components, such as compressor blades, it was found that the endurance limit was not affected by aqueous solutions. Fracture energy also was unaffected by steam. Aqueous stress corrosion has not been a problem in either the J58 or TF30 engines, both of which have Ti-8Al-1Mo-1V titanium components.

As a result of inconsistencies between successful P&WA engine operation experience and several laboratories' tests simulating environmental effects on Ti-8Mo-1Mo-1V, P&WA fracture toughness testing has been expanded to current compressor alloys, Ti-6Al-4V, and AMS 6304 low alloy steel. These alloys were found to be as susceptible to aqueous degradation of fracture strength as Ti-8Al-1Mo-1V alloy; it is significant that millions of engine hours have been accumulated on parts made from these alloys without experiencing aqueous stress corrosion failures. This indicates that the study of fracture mechanics using 2-inch cracks in large specimens, as is done to simulate potential problems with pressure vessels and tanks, may not be applicable to turbo machinery. Work is in progress at P&WA to further the understanding of fracture mechanics as it applies to gas turbines, with special emphasis on understanding crack initiation in engine components and alloys as well as on the effect of plastic deformation at the crack tip.

A third type of corrosion is a surface attack of titanium alloys at elevated temperatures by oxidation or absorption of hydrogen and/or nitrogen. These general forms of attack are primarily associated with forging or heat treatment practices but are experienced also after long time operation above 800°F. The possible general degradation of surface properties in components operated at elevated temperatures has long been recognized by P&WA. To evaluate this phenomenon, creep specimens exposed for various lengths of time over a range of temperatures and stresses are evaluated by room temperature tensile tests after the exposure. Although degradation in room temperature ductility is noted for virtually all titanium alloys after long time exposure above 800°F, this loss is not regarded as a significant factor in titanium alloys used by P&WA in existing commercial engines. However, in view of the stringent operating condition of the JTF17, we believe that every effort must be made to render this alloy immune to surface attack.

As a result of this belief, intensive development has been performed that has evolved two approaches of immunizing the surface from environmental attack. These are the introduction of compressive residual stresses and the coating of components. Glass bead peening has shown very promising results for Ti-8Al-1Mo-1V as well as for other titanium alloys, as shown in figure 3. Because stress analyses of structures have shown that the stresses induced by glass bead blasting are 95% relieved after less than 10 hours at 800°F, the more than twofold increase in stress required to induce stress corrosion cracks in 100 hours at 800°F is difficult to explain in terms of residual stress, per se. Studies of the mechanisms of stress corrosion crack initiation are in progress that should aid in understanding the reason glass bead peening increases stress corrosion resistance at elevated temperatures.

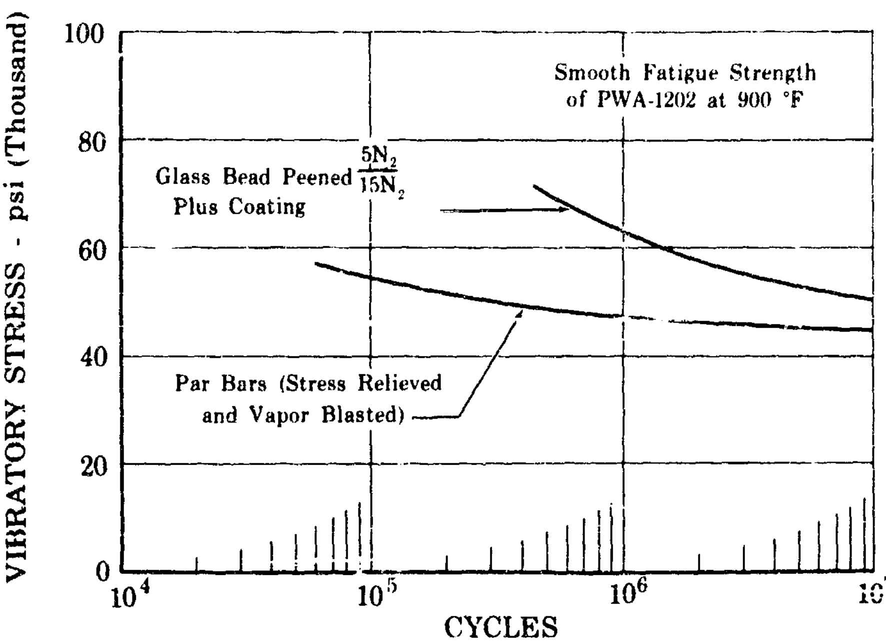

Figure 3. Effect of Glass Bead Peening and Coating on Fatigue Strength of PWA-1202

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FII

Very recent evaluations have shown the combined benefits of surface peening with the previously mentioned P&WA coating system. This system consists of an aluminum pigment and a semi-organic matrix which decomposes and chemically bonds to the titanium basis metal. This coating protects against surface oxidation during elevated temperature exposure and also provides improvement in room temperature fatigue strength, figure 4. In addition, preliminary testing of coated specimens at 900°F for 150 hours in salt shows that the "no crack" stress is increased fourfold (figure 5).

Visual examination of a coated compressor blade subjected to vibratory stresses on a shaker rig for 100 hours at 900° shows the coated surface to have pretest luster and integrity. Improvements in the present coating system are desired; these should result from further study, which includes full-scale engine testing, chemical synthesis, and investigations aimed at improving present as-applied formulations. The

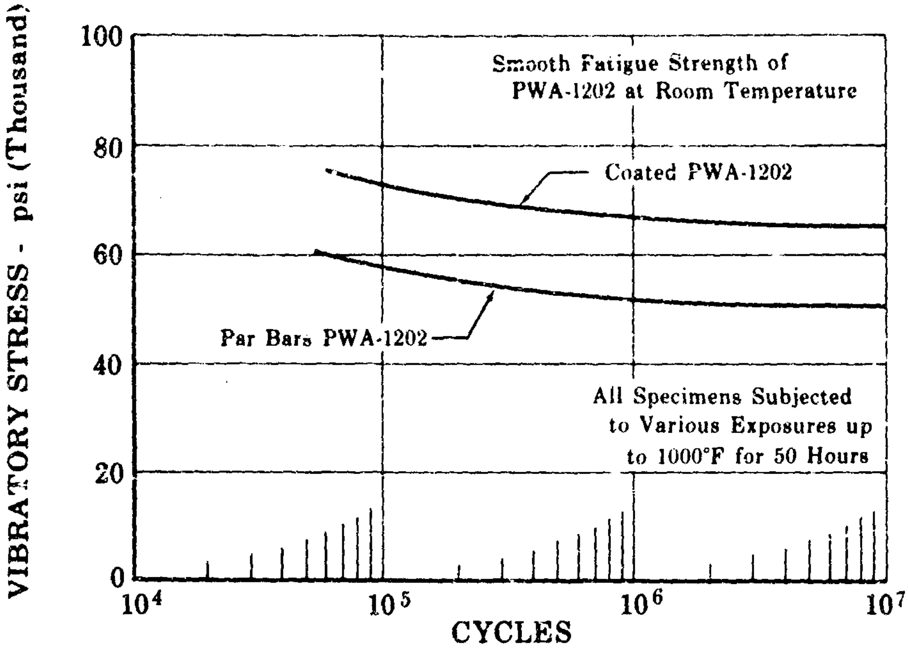


Figure 4. Effect of Coating on Fatigue Strength of PWA-1202 Specimens FD 16575 FII

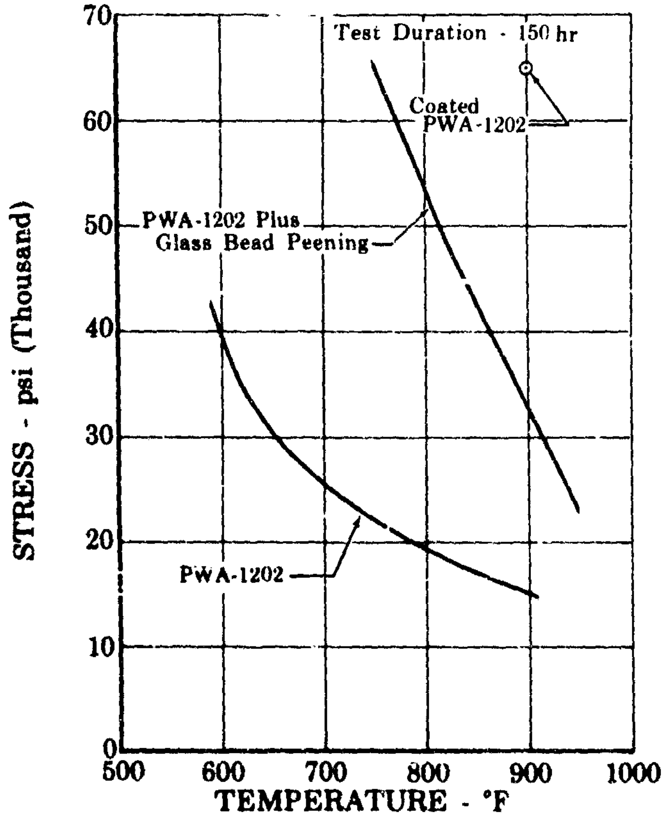


Figure 5. Effect of Surface Treatments for Accelerated Salt Corrosion of PWA-1202 FD 16576 FII

purpose of this work is to offer complete surface protection (oxidation and corrosion) to several titanium alloys, which will allow the alloys to operate to their maximum temperature-strength capabilities.

Additional evaluation to determine the ability of the coating to withstand the scrubbing action of high velocity air is underway to explore the limitations of this coating system. Even if the coating should prove to be limited to static components subjected to low velocity air, the coating would still find extensive use in the JTF17 and provide an improvement in reliability.

(3) Melting and Forging Development

P&WA has sponsored a continuing development effort involving PWA-1202 (Ti-8Al-1Mo-1V) alloy in cooperation with general development of the alloy by the titanium industry. Discussions of currently active programs follow.

P&WA has found it necessary to establish constant surveillance of melting practices for production alloys such as Ti-6Al-4V, and these controls have been expanded to include all new compositions of titanium. Titanium alloys used in gas turbine engines are conventionally double consumable vacuum melted. This practice has, in general, provided high quality, segregation-free material; however, Ti-6Al-4V alloy, which has been produced in tonnage quantities for several years, even recently has been found to contain rejectable segregation in forgings from specific heats of material. P&WA has, therefore, insisted on the introduction of triple vacuum melting to control segregation; results of a large number of such heats now being made will be evaluated during 1966.

In addition, steps have been taken to eliminate the segregation through implementation of tighter controls on raw materials and master alloys, elimination of welding of secondary ingots, improvement of ingot surface condition, and tightening of sonic inspection standards. The non-destructive testing of titanium alloy components and the development of improved testing techniques are also an integral part of this program. These same controls have been applied to Ti-8Al-1Mo-1V to prevent similar occurrence. Studies are in process to evaluate the ability of different forging practices to eliminate or minimize areas of segregation.

Recent investigations by P&WA of Ti-8Al-1Mo-1V alloy forged at temperatures near and slightly above the beta transus have shown that two important material properties, creep strength and fracture toughness, can be improved by this practice. This improvement also has been shown by Ti-6Al-4V. Creep tests of Ti-8Al-1Mo-1V at 850°F and 50,000 psi have shown an average life of 17 hours to 0.1% creep for specimens from material forged below the beta transus. Creep specimens from identical forgings produced from the same heat of material but forged above the beta transus showed an average life of 103 hours to 0.1% under the same conditions as above. Precracked Charpy slow bend fracture energy tests conducted on Ti-8Al-1Mo-1V have shown an increase from nominally 400 in-lbs/in^2 for alpha-beta forged material to over 700 in-lbs/in^2 for beta forged material. Despite these encouraging results, the use of beta forged titanium must be considered developmental until reliability has been demonstrated by development engine testing for commercial engines. "Beta forging" causes a modest reduction (about 15%) in room temperature tensile ductility; however, in view of the increased fracture toughness and inherent high ductility of titanium alloys, this factor is not considered to be significant.

(4) Welding Development

Ti-8Al-1Mo-1V has good weldability, similar to that of highly weldable A-110AT. In welding development, P&WA has conducted extensive investigations of Ti-8Al-1Mo-1V alloy and has evolved techniques for the fabrication of the welded components specified for the JTF17 engine. A welded and fabricated component for the TF30 engine is shown in figure 6.

In the welding of Ti-8Al-1Mo-1V sheet, the duplex annealed condition will be used. This condition is accomplished by subjecting a mill annealed sheet to a short time (15 minutes) 1450°F treatment, followed by air cooling. The mill annealed condition is a 1450°F heat treatment also but is terminated by furnace cooling. This duplex annealed condition provides maximum notch toughness with only a slight sacrifice in strength when compared to single mill annealed sheet material. Welds in the duplex annealed material have exhibited strength and ductility closely approaching those of the duplex annealed base metal at test temperatures from room temperature to 950°F. The weld development program conducted by P&WA has involved restrained weldments and welded panels, all of

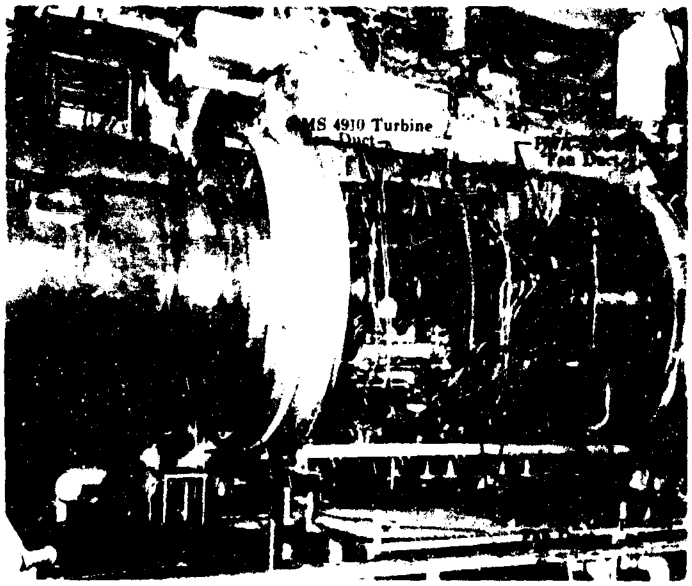


Figure 6. PWA-1202 Welded Components Used for the TF30 Engine   FD 16577 FII

which have been subjected to X-ray and microstructural examination. The restrained weldments were subjected to various heat treatments in an attempt to induce cracking; no cracks were formed.

Based upon this investigation it has been established that Ti-8Al-1Mo-1V is a readily weldable alloy, and the weldments of the alloy can be subjected to various additional heat treatments without cracking when normal precautions are employed.

b. AMS 4910, AMS 4926, and AMS 4966 (A-110AT)

AMS 4910, AMS 4926, and AMS 4966 (A-110AT) are alpha titanium alloys that have been specified for components in the JTF17 engine as follows:

Mount Ring	Fan
1st and 2nd Case	Fan
1st and 2nd Case	Fan
Case	Intermediate Case
Duct Diffuser	Intermediate Case
Split Diffuser	Fan Duct
Duct Burner Support	Fan Duct
Outer Duct, Rear Cone	Fan Duct
Outer Rear Skin	Fan Duct
	Reverser-Suppressor

(1) Substantiation

Titanium alloy AMS 4910, AMS 4966, AMS 4926 (A-110AT), specified for use in the P&WA JTF17 engine, is currently in tonnage quantity use for welded compressor components on production commercial and military engines. Various major components fabricated from A-110AT include the intermediate compressor cases, low compressor cases, inlet vanes, inlet cases, and fan cases. These components are used in P&WA J57, JT3, J75, JT4, TF30, and J58 engines and have compiled an enviable record in reliability.

This alloy is used in stationary parts requiring formability and weldability with higher strength than commercially pure titanium. A-110AT, not hardenable by heat treatment, has excellent weldability and has strength superior to that of AMS 4901 (commercially pure titanium) at temperatures up to 800°F. The tensile strength of A-110AT is inferior to that of AMS 4928 (Ti-6Al-4V) and PWA 1202 (Ti-8Al-1Mo-1V). The creep strength of A-110AT is superior to AMS 4928 (Ti-6Al-4V) at temperatures above 800°F, but inferior to PWA-1202 (Ti-8Al-1Mo-1V) at all temperatures. Its oxidation resistance is good at temperatures up to 1000°F.

(2) Process Development

To make A-110AT a production material, many metallurgical and fabrication problems had to be overcome. These problems were solved through the efforts of P&WA in cooperation with the titanium suppliers. Processing accomplishments in the use of A-110AT have included hot forming, prevention of surface contamination due to intersititial absorption during heating, welding under inert gas cover, and super cleaning to avoid stress corrosion cracking during stress relieving heat treatments. The development of special fabricating and joining techniques required for complex, highly stressed gas turbine sheet metal and forged assemblies was a major achievement.

An example of welding technique developed for the fabrication of large complex weldments is shown in figure 7, which is an enclosed chamber used for welding a large J58 inlet guide vane assembly. The chamber contains inert gas with entry ports provided for operator access to various sections of the weldment. Figure 8 shows a completed complex variable inlet guide vane assembly of A-110AT alloy for the J58 engine.

Figure 7. Welding Technique Developed to Fabricate a Large Weldment of AMS-4926(A 110AT). Part Being Welded is a Large Inlet Vane and Case Assembly.

FE-58840
FII

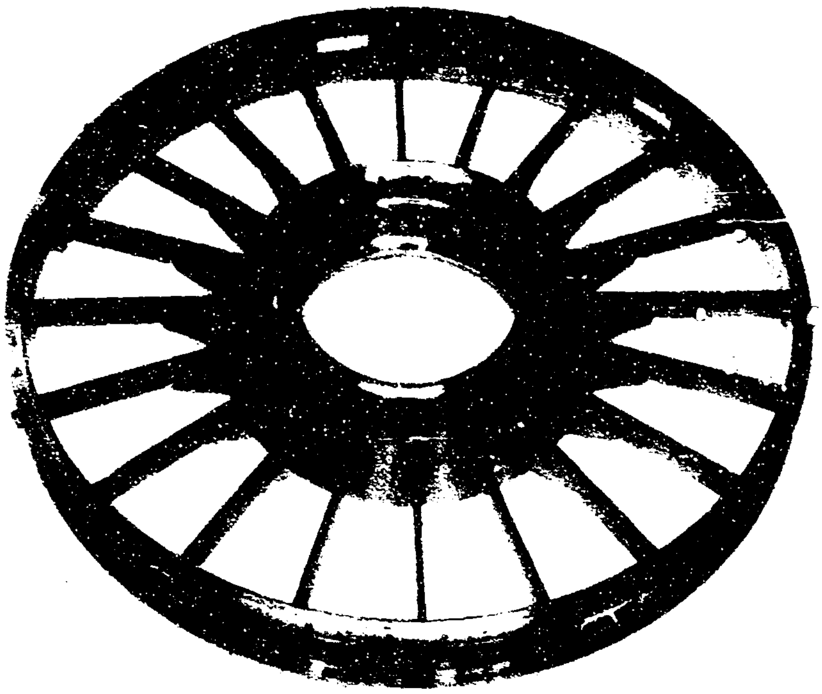


Figure 8. Completed Weldment of a Variable Inlet Guide Vane Assembly Fabricated from AMS-4926 (A 110AT) FE 58838 FII

c. AMS 4928, AMS 4935, AMS 4911 (Ti-6Al-4V)

AMS 4928, AMS 4935, AMS 4911 (Ti-6Al-4V) is a high alpha, low beta composition specified for the following JTF17 components:

1st and 2nd Stage Blades	Fan
1st and 2nd Stage Vanes	Fan
1st Disk	Fan
Duct Exit Guide Vane	Fan
Housings	Gearboxes

(1) Substantiation

Ti-6Al-4V alloy was introduced to industry in 1954 and is generally regarded today as the work horse alloy of the titanium industry. P&WA has used the alloy extensively in the past, primarily for compressor disks, blades, and tie bolts. The alloy is used in the annealed condition for creep stability and improved tensile ductility.

Ti-6Al-4V is superior in tensile, creep, and stress rupture strength to AMS 4926 (A-110AT) to 750°F, but inferior to PWA 1202 (Ti-8Al-1Mo-1V) at all temperatures. Ti-6Al-4V has excellent oxidation and general corrosion resistance, with superior stress corrosion capability to PWA-1202 (Ti-8Al-1Mo-1V) up to the Ti-6Al-4V maximum operating temperature limit of 750°F (figure 2). It also exhibits superior forgeability to most titanium alloys. Ti-6Al-4V has been available for many years in production tonnages as bar or forgings (AMS 4928), sheet, strip, or plate (AMS 4911) and extruded bars, rods, and shapes (AMS 4935). The alloy is commonly fabricated using conventional titanium practices.

3. Proposed Alloys - Advanced Development

a. PWA-1205 (IMI 679)

PWA-1205 (IMI 679) is a new complex superalloy developed in 1959 with improved properties at elevated temperatures. The advantages of the alloy are a high tolerance for hydrogen, excellent creep properties, freedom from high temperature embrittlement, good tensile properties, and good forgeability.

The use of PWA-1205 (IMI 679) in this country has been limited to experimental engine development parts. P&WA first tested 14 inch diameter pancakes forged as early as 1961. In 1964, two leading forging vendors forged TF30 engine rear hubs and compressor disks for laboratory evaluation. These forgings were produced from a double consumable vacuum arc remelted billet. These two vendors reported the alloy to have better forgeability than PWA-1202 (Ti-8Al-1Mo-1V). A third vendor has made over 150 1st- and 2nd-stage PWA-1205 (IMI 679) compressor blades for laboratory evaluation and testing in the J58 engine. Based on the test results obtained from these parts, all three forging vendors agree that PWA-1205 property requirements can be met in longitudinal as well as transverse directions. P&WA has tested material from two suppliers and has found both to be of equal quality.

Long-time, steady-stress exposure of PWA-1205 (IMI 679) in the laboratory using a "caked on" salt (sodium chloride) and still air environment can produce stress corrosion cracking and pitting, but no stress corrosion failures of IMI 679 have occurred in British engines, although the alloy has been operating at 850°F to 900°F in these engines for many hours. P&WA fatigue studies were made using both salted (3.5% NaCl) Krouse rotating beam smooth fatigue specimens and unsalted specimens. Results shown in figure 9 indicate that the 900°F smooth fatigue strength of salted PWA-1205 (IMI 679) is somewhat lower than unsalted specimens, but higher than non-salted PWA-1202 (Ti-8Al-1Mo-1V).

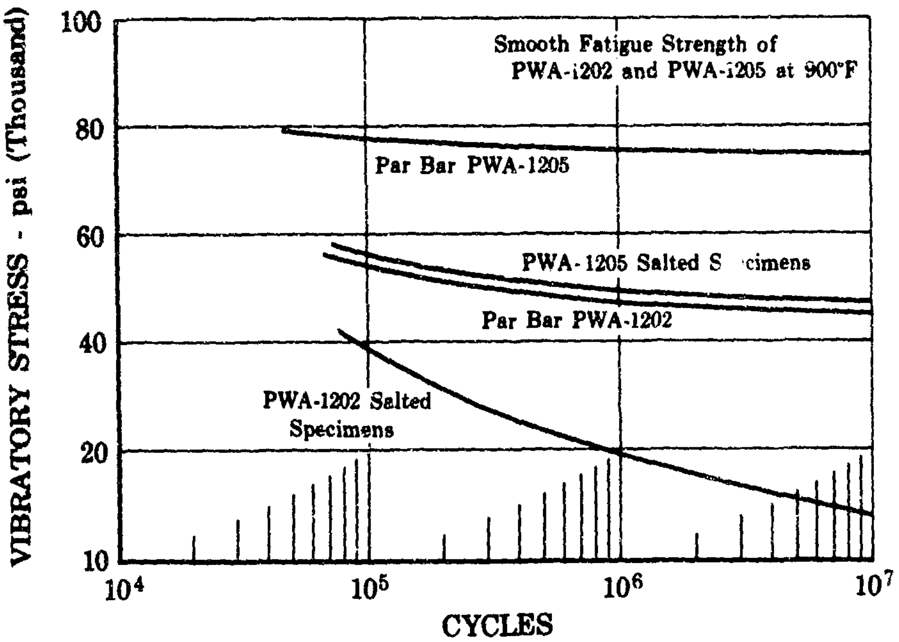


Figure 9. Effect of Salt on Fatigue Strength of PWA-1202 and PWA-1205 FD 16578 FII

The PWA-1205 (IMI 679) alloy also shows a high degree of resistance to changes in mechanical properties after long time exposure with stress at temperatures 900°F. These property changes, which result in low room temperature tensile ductility after the stress/temperature exposure, occur in most other high strength titanium alloys at 900°F. The loss in ductility occurs from the formation of embrittling structural phases or from surface embrittlement caused basically by oxygen, hydrogen, or nitrogen adsorption. Tests up to 1000 hours duration at 900°F on forged compressor disk specimens at a forging compressor disk specimens at a forging company, tests at P&WA on specimens from bar-stock and blades, and tests by the British after long time engine operations all substantiate the long time stability of the alloy.

J58 parts of PWA-1205 (IMI 679) have been tested to determine the performance of PWA-1205 (IMI 679) parts exposed to simulated engine conditions. First-stage J58 compressor blades have been loaded at a constant stress at 900°F in their root areas and fatigued to failure;

the blades subjected to these combined load conditions show good fatigue strength characteristics. Similarly, the alloy has been subjected to fretting fatigue conditions occurring from high bearing and vibratory stresses and gives excellent performance at 900°F relative to other titanium alloys and to nickel base alloys, such as Waspaloy. The ability to resist fretting fatigue is necessary when highly stressed parts of similar or dissimilar alloys are in contact with each other under cyclic conditions.

P&WA testing indicates that PWA-1205 (IMI 679) has good strength properties to 900°F; in spite of the higher density (0.174 lb/in.^{3}) it exceeds PWA-1202 (Ti-8Al-1Mo-1V) on a strength-to-weight basis. Some PWA-1205 (IMI 679) 1st stage compressor blades are being endurance tested in J58 engines; however, insufficient time has been obtained on these parts to determine their relative performance in comparison to other alloys.

P&WA has begun a comprehensive program on PWA-1205 (IMI 679) to determine the effect that heat treatment and forging temperature have on critical design parameters for disks and blades. Forging variables include forging well above the beta transus, slightly above the beta transus, in the alpha plus beta region slightly below the beta transus, and within the alpha plus beta field just above the alpha transus. Heat treatment variables include air cooling from above the beta transus, air cooling and oil quenching from within the alpha plus beta field, and air cooling from a temperature close to the alpha transus. Test parameters are stress corrosion, creep, creep stability, tensile strength and ductility,low cycle fatigue, fracture toughness, fretting fatigue, rotating beam fatigue, and combined stress fatigue.

P&WA is also considering the alloy for weldment assemblies. Sound welds both restrained and unrestrained have been made with no difficulty.

b. Titanium 6Al-2Sn-4Zr-2Mo

Ti-6Al-2Sn-4Zr-2Mo is a super-alpha titanium alloy developed in 1965 by a titanium producer and is being considered by P&WA for service to 1050°F. Recent additions of silicon to the alloy have resulted in excellent creep characteristics when the alloy is forged above the beta transus region.

The density is 0.164 lb/in.^{3} versus 0.174 lb/in.^{3} for PWA-1205 (IMI 679). The alloy is being consid ed as a possible candidate fc blades, disks, and cases, and the recommended heat treatment is 1650°F (1 hour) AC + 1100°F (8 hours) AC.

No production Ti-6Al-2Sn-4Zr-2Mo parts have been made, but two forging vendors have made three hammer forged 18 inch compressor wheels from the alloy. Both companies report the alloy to have excellent forgeability. Examination of material properties indicates that the alloy has superior elevated tensile strength and stress rupture strength; and equal creep, fatigue strength, and fretting fatigue to PWA-1205 (IMI 679). On the basis of strength-to-weight the alloy is considerably better than PWA-1205 (IMI 679) or PWA-1202 (Ti-8Al-1Mo-1V). An addition of 0.15% silicon to the alloy by the metal producer has resulted in a substantial increase in creep strength in the 850°F to 1000°F temperature range.

Producer and P&WA test data indicate that the alloy has good property stability after 1000 hours at 950°F and 1000°F temperatures. PWA-1205 (IMI 679) under similar conditions has a decreased post tensile elongation and reduction of area below 10%. PWA-1205 (IMI 679) is being considered for temperatures only to 900°F unless continued development on coatings, processing and heat treatment improves the alloy's stability.

Ti-6Al-2Sn-4Zr-2Mo is more susceptible to stress corrosion than PWA-1205 (IMI 679), but it is considerably better than PWA-1202 (Ti-8Al-1Mo-1V). The addition of silicon and changes in the microstructure by forging and heat treatment is planned to improve the alloy's stress corrosion capability.

P&WA has initiated a forging and heat treating program on Ti-6Al-2Sn-4Zr-2Mo and Ti-6Al-2Sn-4Zr-2Mo + silicon similar to that indicated for PWA-1205 (IMI 679). The program should provide sufficient information on the suitability of the alloy for JTF17 applications.

The alloy is also being considered for welded assemblies. The alloy producer indicates that Ti-6Al-2Sn-4Zr-2Mo is equivalent in weldability to AMS 4928 (Ti-6Al-4V). A comprehensive welding program is being conducted by P&WA to determine the welding and property characteristics of Ti-6Al-2Sn-4Zr-2Mo sheet.

c. Hylite 60

Hylite 60 is an alpha-beta alloy containing additions of 6% tin, 5% zirconium, 3% aluminum, 2% molybdenum and 0.5% silicon. The alloy is similar in composition to PWA-1205 (IMI 679) and was designed specifically for gas turbine blades and disks seeing service to 950°F. The density of 0.172 lb/in.^{3} is similar to PWA-1205 (IMI 679).

The alloy is being considered by P&WA on the basis of its exceptionally high 0.1% creep strength and its stability for long times to 950°F. To obtain the high creep strength properties, the alloy is solution treated above the beta transus at 1830°F, then stabilized or aged for 24 hours at 1020°F. Hylite 60 has a higher aging temperature than PWA-1205 (IMI 679), indicating that the stability of the alloy above 900°F may also be better.

No stress corrosion data are available on Hylite 60; but with a chemistry basically similar to that of PWA-1205 (IMI 679), it is assumed that its stress corrosion resistance would also be similar.

The alloy was developed by a metal producer in 1963. It has not been used in tonnage quantities by British engine manufacturers as has PWA-1205 (IMI 679); therefore, the alloy's long time performance at elevated temperatures is not known. P&WA has done a limited amount of testing on the alloy, but a comprehensive program similar to that on IMI 679 and Ti-6Al-2Sn-4Zr-2Mo is now being conducted.

Hylite 60 is compared to the previously two described alloys, PWA-1205 (IMI 679) and Ti-6Al-2Sn-4Zr-2Mo, in table 1.

Table 1. Comparison of Proposed Titanium Alloys

Alloy	Max Usable Temperature	Relative Resistance to Stress Corrosion	Relative Structural Stability
IMI 679	900°F	A	B
6-2-4-2	1050°F	B	A
Hylite 60	950°F	Assumed A	B

d. 1200°F Titanium Alloy

In the course of providing materials for PWA nuclear powered engines, light weight designs resulted in the investigation of new titanium alloy compositions. The objective of this work was the development of a titanium base alloy with useful strength to 1200°F. A number of solid solution-dispersion strengthened combinations were evaluated. The most promising of these were alpha alloy systems using aluminum, zirconium, and carbon. The best combination of strength and ductility was achieved when material was worked entirely below the beta transus and heat-treated to produce a fine carbide dispersion. During this effort ingots up to 4 inches in diameter were extruded to rod or forged and rolled to sheet. The bulk of the testing was performed to meet the nuclear application at 1200°F; however, the desire by P&WA to use the high strength-to-weight ratio of titanium has resulted in a transfer of this effort for use in conventional engines for 900°F to 1200°F uses. The preliminary data on this alloy are encouraging, and testing is in progress on additional material manufactured in 1966 to the redefined application. The forging sequence of the alloy has considerable effect in adjusting of properties. A favorable room temperature ductility, the lack of which is the bane of most ultra high temperature titanium alloys, may reach a maximum when the alloy is heat treated in the vicinity of the alpha plus beta transformation temperature. Additional work is continuing to explore the ramifications of these findings.

e. Titanium Tubing

Titanium alloy tubing is being considered as a replacement for iron and nickel base tubing in the JTF17 engine. This will decrease total engine weight by approximately 90 pounds. Tubing strength will increase using the same sizes as specified for iron base tubing.

P&WA has recently been engaged in a development program to substitute titanium tubing for austenitic stainless steel tubing. The objective of this program is to fabricate titanium tubing that exhibits properties, particularly fatigue, comparable to the materials now in use. In addition, titanium tubing fabrication techniques must be developed which will permit the production and use of the integral ferrule couplings which have been developed and used successfully by P&WA on the J58 engine.

The development program has shown that the integral ferrule coupling concept can be applied to titanium tubing. (See figure 10.)

Commercially Pure Titanium Tubing Showing as Formed and Machined Integral Ferrules on Alternate Ends

Ti-3AL-2.5V Alloy Tube Fatigue Specimen Showing Machined Integral Ferrule (Extreme Right)

Figure 10. Examples of Integral Ferrules on Titanium Tubing — FD 16947 FII

Currently, the program involves the use of two titanium alloys; Ti-3Al-2.5V and Ti-6Al-4V. Preliminary work indicates that the fabrication of the integral ferrule can be accomplished and that the fatigue strength will meet the values required for a replacement tubing material offering a significant weight saving.

f. Cast Titanium Alloy Gearbox Housings

Cast Ti-6Al-4V is proposed for the future JTF17 gearbox housings because of production advantages that cast configurations offer over complicated wrought fabricated designs. As a result, cast Ti-6Al-4V housings in future engines are expected to realize significant economic advantages over wrought fabricated housings currently specified for the JTF17 design. Due to technological considerations, however, titanium casting development will be required, and for this reason P&WA is developing and stimulating development in titanium casting technology.

Preliminary work on cast housings is encouraging. Figure 11 shows a housing for the J58 exhaust nozzle control that is cast from A-110AT alloy. This part will be engine tested in the near future. The technology gained from this effort will be applied to cast gearbox housing of Ti-6Al-4V for the JTF17.

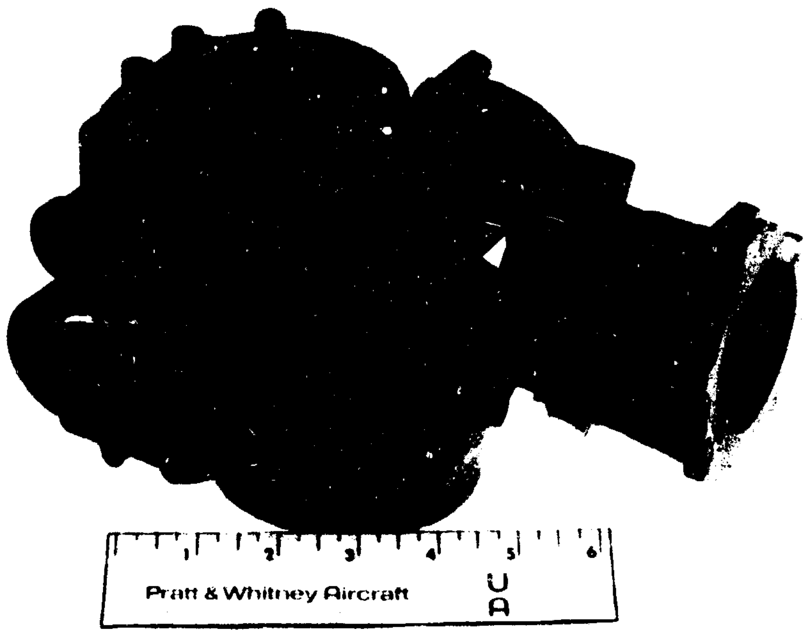


Figure 11. Complex J58 Cast A-110AT Actuator Housing — FAE-61377 FII

Typical tensile and stress rupture properties generated to date on cast Ti-6Al-4V parts are as shown in tables 2 and 3.

Table 2. Typical Stress Rupture Properties

Test Temp, (°F)	0.2%YS Ksi	UTS, Ksi	% El	% Ra
400	86.0	107.0	14.5	32.6
600	68.0	92.5	13.0	37.0
800	67.8	87.5	14.5	35.0

Table 3. Typical Tensile Properties

Test Temp, (°F)	Stress, Ksi	Hours to Rupture	El
850	75.0	301.0	15.0
850	80.0	89.0	13.0

Through an expanding program of development, P&WA will continue to advance the state of titanium casting technology. Results of this technology will make possible reduced costs in areas currently dominated by wrought fabricated configurations.

C. HIGH-SPEED TOOL STEELS

1. Introduction

The gears and bearings in the JTF17 engine must operate successfully for long periods of time at relatively high speeds. The selection of materials that can function with reliability under these conditions is of utmost importance. The bearings and gears will be operating with lubricant temperatures of 400°F while the temperature surrounding the compartments will range from 630°F to 1000°F. These temperatures require materials above and beyond the capabilities of most current engines with the exception of the J58. Two high-speed tool steels have been selected for use in the more severe service of the latest generation of P&WA engines; these alloys are capable of sustained operation at 600°F.

2. Specified Alloys

PWA-724, PWA-742 (Bower 315) and PWA-725 (M-50) high speed tool steels have been specified for components for the JTF17 engine as follows:

Bearings and Races	-	Intermediate Case
Bearings and Races	-	#3 Bearing Support
Bearings and Races	-	#4 Bearing Support
Gears	-	Throughout Engine

PWA-724, PWA-742 (Bower 315) is a high speed steel of a carburizing grade. It is used in gears and roller bearing applications where SAE 52100, SAE 8620 or SAE 9310 have previously been used, but in this case the higher temperatures encountered make these alloys unusable. The carburized case in PWA-724, PWA-742 (Bower 315) maintains its hardness to higher temperatures than AMS 6260 (SAE 9310) as shown on the accompanying figure 12. In gear applications, PWA-724, PWA-742 (Bower 315) has been extensively used in the J58: for roller bearings it has been used in high temperature areas in the TF33, TF30, FT8D, J75, and J57 engines.

PWA-725 (M-50), another high speed tool steel, is used for bearings requiring high hardness and compressive strength at temperatures up to 600°F. Its high fatigue life at elevated temperature is a prime consideration for its use. It was first used in the JT8 and later in some models of the J57 and J75 to replace SAE 52100 which was found to be marginal. These applications involve 5 to 6 years of productions experience. The TF30 and J58 also use bearings of this material.

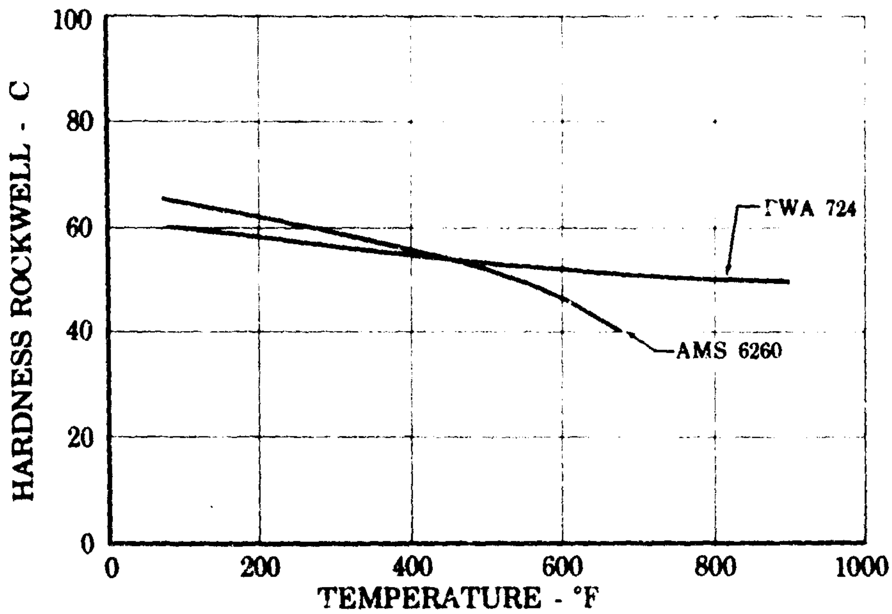


Figure 12. Hot Hardness of Bearing Alloys vs Temperature FD 16579 FII

Changes in the methods of melting have increased by a large factor the mean fatigue life of PWA-725 (M-50). In the beginning, aircraft quality air melted material was used which has a mean fatigue life two to three times that of the material normally used in commercial bearings. Vacuum melting increased the mean fatigue life (although there was considerable scatter in some test lots), and a further increase was accomplished using vacuum consumable electrode melting technique. By the changes in melting practices, the mean fatigue life was increased to ten times that of the original air melted material.

Bearing development testing is conducted at P&WA both on elemental rigs and full-scale engines. Elemental rig testing is used in the evaluation of materials and melting techniques, lubricants, and processing effects, as well as the possible interactions of these effects or conditions. Over 200,000 hours of rig evaluation have been conducted to these ends. Candidates from these evaluations are tested as full-scale bearings. Endurance testing at overload conditions are conducted for a minimum of 100 hours while some tests are run to 1000 hours. Over 50,000 hours of testing have been accumulated in this manner.

P&WA requires that bearing races have controlled grain flow. Testing has shown this condition to give greater bearing life. In addition to the grain flow requirement, carbide segregation is also controlled. Finished bearings are subjected to retained austenite determinations and are accepted only if they meet rigid P&WA standards.

The high temperature environments have also required a new cage material. Here P&WA has found AMS 6414 (SAE 4340) to be a satisfactory material in the J58 engine.

D. WROUGHT NICKEL BASE ALLOYS

1. Introduction

Wrought nickel base superalloys are used in a large number of components in the JTF17 engine. They fall into three general classes. The first class is the high strength, precipitation hardened alloys that are strengthened through heat treatment with aluminum and titanium additions or columbium additions; they are used at temperatures up to approximately 1400°F. The second class of alloys is the solution hardened materials that are not as strong but have excellent oxidation resistance and good long time stability at temperatures up to approximately 1800°F. The third class is the dispersion hardened alloys that are strengthened by minute insoluble oxide particles that are very stable at operating temperatures up to 2400°F. The third class of alloys maintains a level of usable strength at temperatures much higher than the first two classes.

2. Specified Alloys

a. PWA-1013

PWA-1013 (Astroloy) is the strongest known nickel base superalloy used for forgings in a free world production engine. This alloy is one of a group of alloys falling within the wide chemistry range of U-700. On the basis of elevated temperature capability, the alloy shows the same magnitude of improvement over Waspaloy and Rene'41 that these alloys show over Incoloy 901 and V57.

Based upon the superior properties of Astroloy over all other production nickel base forgings alloys, and the outstanding performance of the alloy in the J58 engine, it has been specified for the following components of the JTF17 engine:

First Stage Disk - Turbine
Second Stage Disk - Turbine
Third Stage Disk - Turbine
Bolts - Turbine

(1) Background and Experience

The use of Astroloy for engine components has been diligently pursued by P&WA. It is currently in use in the J58 engine for turbine and compressor disks, disk spacer rings, and bolts. It is also now undergoing engine tests in sheet and ring form as a welded assembly. Finally, its close relative, U-700, has found extensive use in P&WA's engines with millions of hours of engine operation having been logged. Astroloy turbine and compressor disks have performed most successfully in the J58 engine. This experience has demonstrated the outstanding capability of the alloy and substantiates its suitability for turbine disk application for the JTF17 engine. In the J58 engine, Astroloy disks have been subjected to very high operating temperatures and stresses and, most important, to severe thermal gradients from rim to bore on a cyclic basis as a function of frequent and rapid airplane and engine accelerations and decelerations. Under these most severe conditions, disks of the alloy have shown low creep growth with no structural instability. Little reduction of original mechanical properties has occurred as evidenced by post engine operation cut-up evaluation, consisting of both mechanical property determination and microstructural review.

Because of its demonstrated capability to endure cyclic abuse, as well as its outstanding elevated temperature creep and tensile strength, Astroloy has been specified for the three stages of turbine disks for the JTF17 engine. At the operating temperatures to be experienced in the JTF17, this alloy will provide a margin of safety for over-temperature that no other production nickel base superalloy can approach.

(2) Disk Development

Early in the development of the J58 engine, it became evident that the strongest of the most advanced disk alloys, Waspaloy and René 41, did not possess the required tensile, creep, and rupture properties for turbine disks. Some very preliminary work bv a forging vendor indicated that a composition referred to at that time as Astroloy had the strength potential required. After evaluating several disks of the alloy from this forging source, it was obvious that a major development program on the part of P&WA would be required to make the alloy usable. Accordingly, in 1961 such a program was initiated; and, since that time, P&WA has been the sole developer and user of Astroloy turbine disks and compressor spacer rings in production engines. A brief discussion of this development of Astroloy to its present level of capability follows.

In 1961, it was apparent that the chemistry being offered by the commercial melting and forging sources was out of balance. There was segregation of extraneous phases which contributed nothing to the strengthening of the alloy and actually reduced the strength and ductility. The heat treatment recommended for large disk forgings (by the melting and forging sources) was the same as that used on small turbine blade forgings and resulted in an extremely coarse grain size which contributed to low tensile strength, low ductility, and low fatigue properties. The uniformity in these early forgings was poor; grain size ranged from ASTM 2 to larger than 1/4 inch (figure 13). A development program was undertaken by P&WA to overcome these material deficiencies to assure that the turbine disks would meet requirements.

In early 1962, P&WA originated, designed, supervised, and sponsored, under the J58 development program, four simultaneous interdependent development programs directed toward improving the characteristics of Astroloy. These were (1) a chemistry modification program, (2) an ingot evaluation program, (3) a heat treat development program, and (4) a forging development program.

(a) Chemistry Modification

The chemistry modification program was arbitrarily set up to cover four levels of aluminum and boron in a factorial experiment made up of 16 heats of material. The boron increments were 0.005%, 0.010%, 0.015%, and 0.020%; the aluminum increments were 3.50%, 4.00%, 4.50% and 5.00%. All other elements were held constant. All 16 heats were weighed at the same time from the same raw material batches and were placed in sealed containers until they were melted. The heat size in each case was 50 pounds. The same furnace and operator was used for all heats.

Each heat of the experiment was poured through a common tundish into two identical ingot molds. One ingot from each heat was cut longitudinally

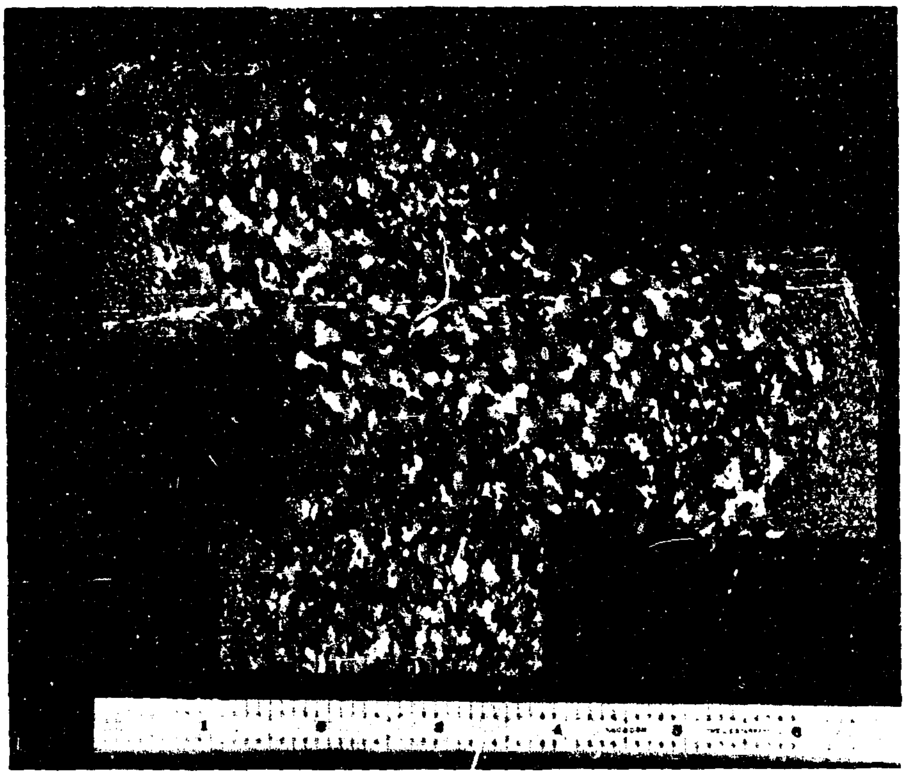


Figure 13. Partial Cross Section of an Early Astroloy Disk Forging Exhibiting Duplex Structure and Very Coarse Grains FML-9293 FII

from hot top to the bottom; the surfaces were ground and etched to determine ingot structure and soundness. The second ingot from each heat was machined for forging. All the ingots were forged using multiple forging operations on a press during a single forging run. A rotary furnace was used so that each ingot was exposed to the same forging temperature for the same amount of time. Kissing blocks were used on the press so that for each forging operation every ingot was reduced the same amount.

Each of the 16 forged pancakes was cut into three equal pie shaped segments. One segment of each pancake was given the heat treatment required by PWA 1006, the then current disk specification. The other two segments of each pancake were set aside to be heat treated later to processes developed by P&WA and the forging vendor. The optimum chemistry for the PWA 1006 heat treatment was 4.5% aluminum and 0.015% boron.

The P&WA heat treatment which was developed to maintain a fine grain size showed the experiment would have to be run to higher boron levels for optimum properties. Seventeen additional heats were added to the experiment at aluminum levels of 3.5%, 4.0% and 4.5% and boron at 0.020%, 0.025%, 0.030%, 0.035% and 0.040%. Four heats with a change in titanium level from 3.60% to 3.25% were a part of the addition to the program.

The optimum composition for both properties and microstructural uniformity was 4.0% aluminum and 0.025% boron. Contour plots showing properties of the completed program are shown in figure 14. As can be seen from these plots, a very small change in the chemistry level of either aluminum or boron can cause a very significant change in the mechanical properties of the alloy over the temperature range investigated. For example, at 0.020% boron the creep life at 1300°F and 74,000 psi decreases from 210 hours at 4.5% aluminum to 27.3 hours at 5.0% aluminum.

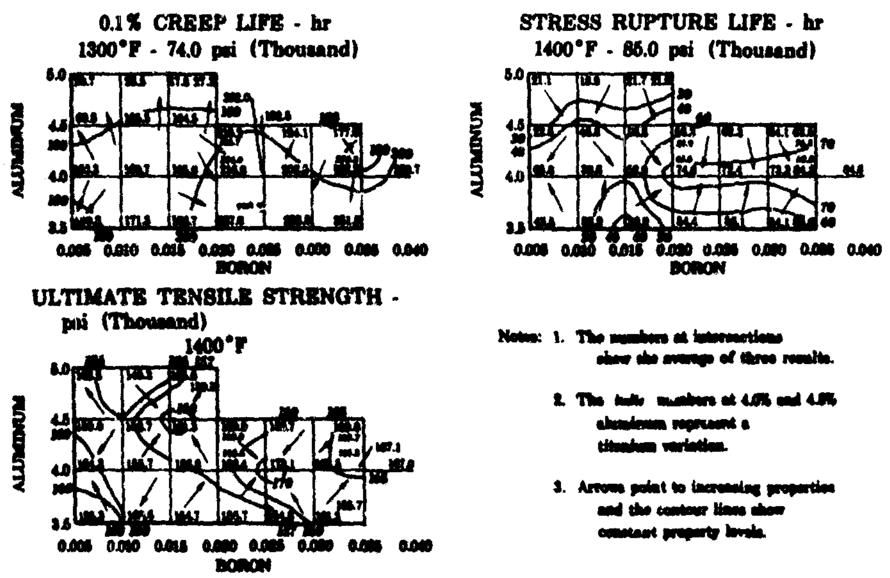


Figure 14. Astroloy Chemistry Modifications Effect on Mechanical Properties FD 16580 FII

The chemistry ranges in the current P&WA Astroloy specification, PWA-1013E, were established by this development program. Although the limits are tight, they have been consistently met by the material suppliers over the past 3 years. These close chemistry ranges have also led to less scatter of properties in forgings that have been properly heat treated.

(b) Ingot Evaluation

Late in 1961, it became apparent to P&WA that at least 90% of all high temperature wrought materials problems could be traced back to poor ingot structure. These problems included low ductility, low strength, cracking during fabrication and heat treatment, and a wide variation in mechanical properties from part to part and within a given part. Metallurgical evidence in the form of micro and macrostructures of material from all major sources was compiled showing that segregation in the ingot was not eliminated by subsequent forging and thermal treatments and was still present in finished parts, (figure 15).

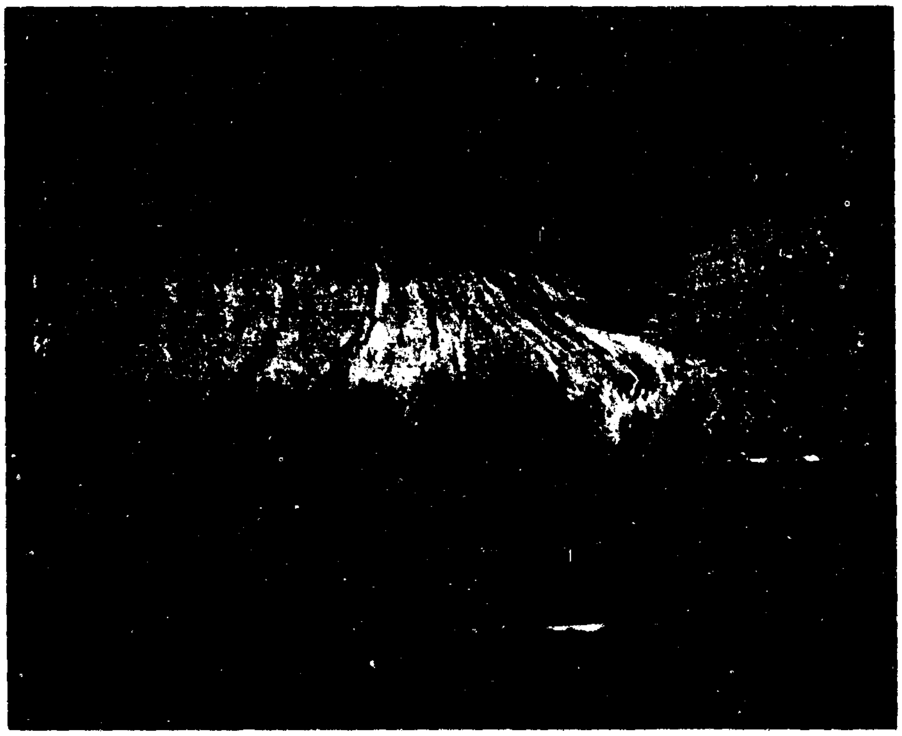


Figure 15. Cross Section of an Astroloy Disk Forging Made From 11-Inch Diameter Billet, Billet Cogged From 20-Inch Diameter Ingot, Exhibiting Remnant Segregation From The Ingot. FML-9294 FII

In February of 1962, P&WA metallurgists visited all of the major materials suppliers and presented the problem to them. As a result of these visits, a cooperative Astroloy ingot evaluation program was drawn up. This program was carried on simultaneously with the Astroloy chemistry and heat treat development program.

Five different melting sources originally took part in this program. The ingots were made by each melting source to their "best" practice. They were split longitudinally from top to bottom, then each half was cut into three equal pieces to show structure, both longitudinal and transverse to the ingot length. The pieces from one half of the ingot were ground and etched to show the macrostructure of the ingot. The other half was ground and dye penetrant inspected to show soundness. Samples were cut from top, bottom, and center sections at the edge, mid-radius, and center-line for microstructural evaluation and chemical analysis. The only two forgings vendors then taking orders for Astroloy forgings sent representatives with P&WA metallurgists to inspect each ingot and establish the best two melting sources for each forging source.

There were three different kinds of ingots evaluated in the program. Three melting sources used the conventional double melt practice of vacuum induction melting followed by vacuum consumable melting. One source used vacuum induction melting followed by consumable melting with the Hopkins slag process. The last melting source used a vacuum induction static case ingot.

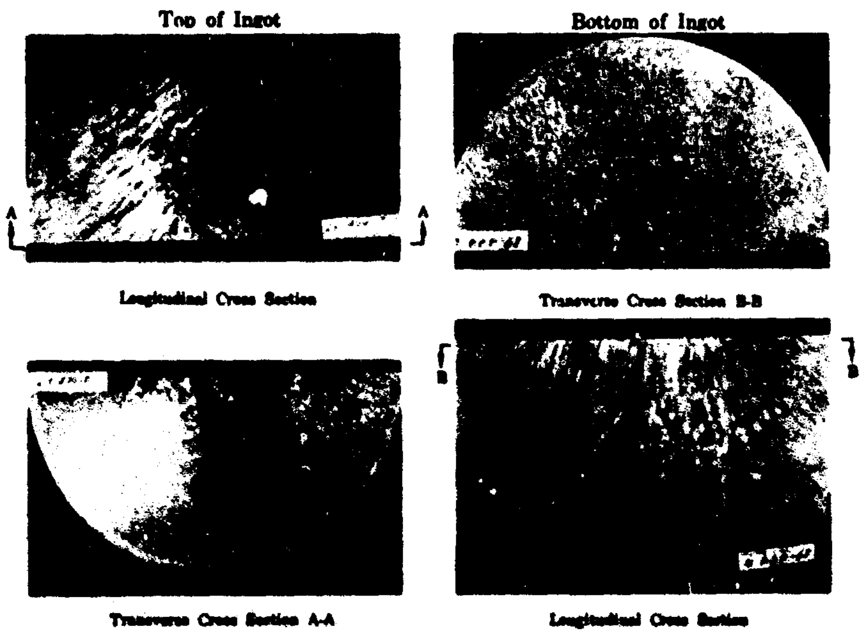
Two of the conventional consumable ingots had nearly identical structure with columnar dendrites (grains) starting at the bottom of the ingot and growing vertically to the top of the ingot. One of these was a 20-inch diameter ingot, the other a 16-inch diameter ingot. They did not show "freckles", a symmetrical pattern of rod-like areas of gross segregation.

The third conventional consumable ingot looked very similar to conventionally static cast ingots with columnar dendrites growing up from the bottom meeting columnar dendrites growing with an upward angle from the side walls. This was also a 16-inch diameter ingot; this structure comprised the bottom two-thirds of the ingot. However, the top third was made up of the columnar structure growing at an upward angle from the side walls and a center section of large equiaxed grains in the form of a cone with the big end up. This type of ingot was very prone to the formation of "freckles". These segregate areas or "freckles" are never broken up in converting the ingot to a finished forging and can be found on the forging by an anodic etch technique. The mechanical properties are greatly reduced in these "freckle" areas of a forging.

The ingot melted using the Hopkin process had a much finer and more uniform structure. This 10-inch diameter ingot was made up of small columnar grains growing at an upward angle from the side walls; a uniform equiaxed center made up about one-half of the diameter. It did not show any "freckles."

The induction melted static cast ingot was 16 inches in diameter. It was cast in a conventional mold using a technique to produce fine grain size. Only the bottom 12 inches of the structure was excellent with a very fine uniform grain size and good soundness. There was secondary pipe throughout the center of the ingot from about 12 inches up from the bottom to the top of the ingot.

Later P&WA metallurgists were shown a cut-up of a consumable ingot from one of the forging sources who do their own melting. It looked equal to the poorest previous consumable ingot seen (figure 16).

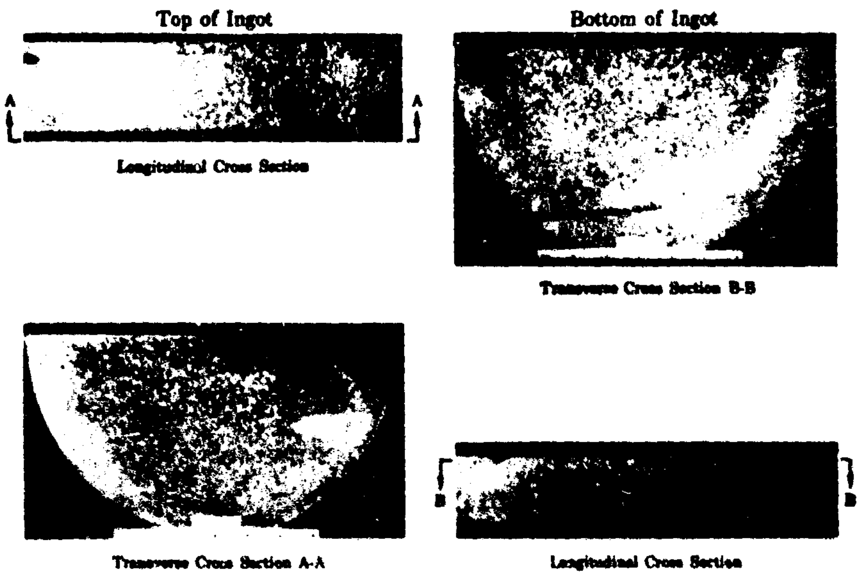


Top of Ingot	Bottom of Ingot
Longitudinal Cross Section	Transverse Cross Section B-B
Transverse Cross Section A-A	Longitudinal Cross Section

Figure 16. PWA-1013 (Astroloy) Sixteen Inch Diameter Ingot Exhibiting Poor Structure — FD 16581 FII

After reviewing the structure in all the ingots previously described, P&WA took the position that if the potential properties of the high temperature alloys were to be obtained there must be a better ingot; namely, one with a high degree of soundness with an ultra-fine equiaxed grain size.

As a result, by late spring of 1963 one melting source which previously was producing an ingot with columnar dendrites growing vertically from bottom to top produced an ingot with structure approaching that requested by P&WA. This ingot was a vast improvement over previous ingots and is still today the standard against which other ingots are judged (figure 17). Today, there are at least three sources capable of making this type of consumable ingot of alloys as complex as Astroloy.



Top of Ingot — Bottom of Ingot

Longitudinal Cross Section — Transverse Cross Section B-B
Transverse Cross Section A-A — Longitudinal Cross Section

Figure 17. PWA-1013 (Astroloy) Twelve Inch Diameter Ingot Exhibiting Good Structure — FD 16582 FII

(c) Heat Treat Development

The heat treatment in use on Astroloy in the fall of 1961 was a carry over from the heat treatment used on U-700 turbine blades. It included a solution temperature that resulted in a coarse grain size. The carbide stabilization and aging temperatures were the same as those used on Waspaloy and most other nickel base precipitation hardened alloys.

To improve the tensile strength, increase ductility, and increase the fatigue resistance of the alloy, a heat treat development program was initiated by P&WA. A microstructure was established that was considered optimum, and a heat treatment program was drawn up to produce this structure.

No mechanical properties were tested during the heat treat development until the structure could be reproduced repetitively on material from several different sources.

The first step of the heat treat development was to establish the gamma prime phase, $Ni_3(Al,Ti)$, solution temperature. Since the material used was from a very broad chemistry range, the solution temperature could vary by as much as 100°F from one sample to another. Also, if the gamma prime was completely taken into solution there was no way to control the grain size on large forgings. Therefore, the solution temperature was established for any given forging just below the grain coarsening temperature. If the solution temperature were too far below the grain coarsening temperature, the degree of solutioning was not sufficient to enhance mechanical properties. With such a tight control on solution temperature, it was seen that uniformity of structure was needed in Astroloy forgings.

The second step of the heat treat development was to establish the carbide stabilization temperature. The upper limit was fairly easy to establish once it was determined that the solution temperature for the secondary (grain boundary) carbides was 1850°F; it would have to be below this temperature. A discrete grain boundary carbide was produced at 1775°F when applied to uniform material, but when nonuniform material was used, no single temperature could be found that would produce the carbide stabilization that was believed necessary. The temperature was then established where the driving force for carbide precipitation was greatest to precipitate as much secondary carbide as possible. Next, the temperature was raised to the point where the carbides would agglomerate into discrete particles. If the grain size could be maintained at ASTM 4 or finer, this two step carbide stabilization of 1600°F for 8 hours, followed by 1800°F for 4 hours, was effective on all material tested.

The third step in the heat treat development was to establish the best aging cycle for parts which were to operate up to a temperature of approximately 1400°F. The low temperature age of 1200°F was established to give the maximum number of gamma prime nuclei. The 1400°F secondary age was to grow the nuclei established at the lower temperature for stability at the part operating temperature.

This heat treatment, which was established completely through microstructural studies on the light and electron microscopes, has produced mechanical properties including room temperature and elevated temperature (up to 1400°F) tensile properties, creep properties (up to 1300°F), and cyclic tensile fatigue properties (up to 1400°F) that are significantly higher than the properties with the previously used heat treatment. The rupture life of the two heat treatments are about the same, but the new heat treatment affords much higher rupture ductility.

(d) Forging Development

The forging development program was drawn up in detail by P&WA and presented to our two Astroloy forging sources. This program used wedges as the starting stock. This geometry allowed reductions from 0% to 70% on the same forging with all other variables being constant. Sufficient wedges were used to examine temperatures from 1850°F to 2200°F, which go beyond the forging limits of the alloy. After forging, the wedges were cut into specimens for heat treat study to correlate the effect of forging reduction with solution temperature. The results of these wedge tests were used to establish temperatures and reduction practice for use on sub-scale (three inch diameter by six inch long starting multiples) disk forgings. These forgings were made in a minimum of three operations with the final thickness being one inch. These small disks produced enough material for mechanical property evaluation of the various forging practices used in the program.

After completion of the above described Astroloy work P&WA procured full-scale J58 turbine disks from the forging vendors representing two material sources from each forging source. These disks were cut up for a complete mechanical property and microstructural evaluation. They represented a large step forward in the development of Astroloy forgings; the properties and structure were much superior to any previous disks that had been examined. A problem still existed with these and subsequent disks with coarse grains and lack of proper amounts of work in the bore area of the disks. This is a condition that has been in existence on high temperature iron and nickel base alloy disks over the years. In some cases, rough forgings are made thick enough at the bore to machine the affected material away. This condition is the result of "die-lock" (remnant structure of the forging multiple occurring on surfaces in contact with the dies where chilling is so rapid that material on the surface does not flow). An example of severe "die-lock" is shown in figure 18. Results of mechanical property tests and engine operation show the condition seriously reduces mechanical properties of a part. P&WA now inspects for this condition and rejects parts showing the condition on the final machined surfaces.

Figure 18. Cross Section of a PWA-1013 (Astroloy) Disk Forged From Fine Grain 12-Inch Ingot Exhibiting Severe "Die Lock" FD 16583 FII

P&WA metallurgists attempting to solve this problem established a forging technique on sub-scale disks which completely eliminated the "die-lock" condition on the "as forged" surfaces. These small disks were uniform in structure from the bore to the rim with no coarse surface grains. The forging vendor who performed this sub-scale work for P&WA received permission to use this technique and subsequently forged 17 J58 disks. One of these disks has been cut up and the rest have had surface grain size determined at sixteen points on the bore and rim. The vendor reports "die-lock" has been eliminated on all seventeen parts. The cut-up disk has been reported by the vendor to have the most uniform structure seen in full size disks (figure 19.) P&WA evaluation confirmed the vendor's reports. It is the vendor's intention to continue to use this forging technique.

J58 Turbine Disk

JTF17 Turbine Disk

Figure 19. Cross Section of Two PWA-1013 (Astroloy) Disks Forged From Fine Grain 12-Inch Ingots — FD 16584 FII

(3) Bolt Development

Bolts required for the highest temperatures encountered in high Mach number engines must be superior to those currently available from bolt manufacturers. P&WA has found that selection of a material with the necessary mechanical properties is not enough; it is imperative that the best microstructure, grain size, processing sequence, and design be utilized for optimum bolts.

An evaluation of Waspaloy bolts was conducted by P&WA; from this work it was determined that the best Waspaloy bolts did not have the required elevated temperature properties above 1300°F for long time operation in advanced engines.

(a) Material Investigation

Astroloy was considered the next logical step in the evolution of high temperature bolts. A base line was established on the best Waspaloy bolts available for stress relaxation, stress rupture, room temperature and elevated temperature tensile strength, and fatigue strength. Astroloy bolts were machined from disk forgings and tested (laboratory and engine tests) against the Waspaloy base line and found to be superior.

Astroloy bar stock of the quality required was not available. P&WA worked with a material supplier and provided metallurgical information to produce bar stock with desired microstructure and grain size suitable for bolts.

(b) Manufacturing Process Sequence

The optimum manufacturing practice for Astroloy bolts was determined. The effect of thread application between different steps of the heat treat cycle, method of thread application, and metallurgical structure were evaluated. Two different grain sizes and two thread designs were used in five bolt manufacturing sequence studies. Only one manufacturing sequence produced satisfactory mechanical and metallurgical properties without thread failures. All other sequences had thread failures during either room temperature and elevated temperature tensile or stress-rupture tests.

(c) Design Investigation

Experimental stress analyses were conducted using Stresscoat, strain gages and three dimensional photoelasticity on several existing and proposed bolt and thread designs to analyze effects of assembly loads, engine centrifugal load, thread load carrying capability, and lubricating and anti-seize characteristics.

The maximum utilization of any engineering material required for high temperature bolts demands the measurement of mechanical properties which previously were either ignored because they were difficult to determine or were estimated from other more readily measured properties. Stress relaxation, the time dependent decrease in stress in a constrained specimen (bolt), is one of these properties.

Machines designed and built by P&WA were used to conduct long duration stress relaxation tests at various temperatures and stress levels. Load is controlled by an electromechanical extensometer (with 90:1 strain multiplication) and servo valve system that maintains constant total strain within five microinches. The load required to maintain constant total strain is detected by a strain gaged load cell and recorded by an oscillograph. Load-time recording gives a stress relaxation curve.

Good stress relaxation data can be used efficiently only if the actual initial assembly bolt stress is known. Therefore, extensive tests were conducted analyzing accepted methods (torque, angle of twist, and elongation) of applying clamping forces between bolt-flange assemblies. These methods do not assure accuracy desired; therefore, P&WA developed a bolt-load indicator capable of more accurate bolt load determination. This indicator also permits determination of stress relaxation occurring during engine runs.

Combined knowledge obtained from these various tests and investigations has significantly improved high temperature, high strength bolting practices. New specifications have been established (PWA-93 Astroloy bolts and PWA-1021 Astroloy barstock) and improvements have been made in bolts of other materials. New or improved materials, manufacturing process sequences, design procedures, and testing techniques have been developed, enabling P&WA to design, manufacture, and place in engine operation optimum high temperature bolts.

(4) Summary

The PWA-1013E (Astroloy) specification has evolved from the four development programs: (1) chemistry modification, (2) ingot evaluation, (3) heat treat development, and (4) forging development described above. This specification and the related quality standards (see Section II-H, Quality Control of Critical Rotating Parts) control chemistry, room temperature and 1400°F tensile properties, 0.10% creep life at 1300°F, 1400°F stress rupture life, grain size at 16 points on each disk, and microstructure as viewed on the electron microscope at 10,000 magnifications. Because of the stringent requirements of the specification, the forgings being purchased to PWA-1013E for the J58 and JTF17 engines are probably the highest quality forgings ever produced for a turbine engine.

b. PWA-1016

PWA-1016 (Waspaloy) is the most widely used alloy on the J58 engine. As shown in table 2 in the Preface, it is present in large forgings as disks, shafts, spacer rings, and cases. It is also used as blades, vanes, fasteners and in welded assemblies of sheet, rings, and forgings. Its history in the J58 engine has been one of outstanding performance; as a result, it has been specified for the following components of the JTF17 engine:

6th through 8th stage blades	High Compressor
3rd through 8th stage disks	High Compressor

Rotor Shaft	High Compressor
Cases, Forward and Rear	Turbine
Spacers	Turbine
Forward Outer Case	Turbine Exhaust
Forward Inner Case	Turbine Exhaust
Rear Outer Case	Turbine Exhaust
Support Cone	#4 Bearing Support
Bolts	Turbine and Compressor

(1) Background

Waspaloy has been in use since the early 1950's. Waspaloy turbine and compressor disks have performed very successfully in the J58 engine. This substantiates its availability and suitability for compressor disk application for the JTF17 engine. The J58 engine subjects disks to very high operating temperatures and stresses and to severe thermal gradients as discussed in the PWA-1013 (Astroloy) section.

Because of its demonstrated capability in the high performance J58 engine, Waspaloy has been specified for the high compressor disks of the JTF17 engine.

The use of Waspaloy in shafts and cases in the J58 engine has been successful, attesting to its availability and suitability for the JTF17 engine.

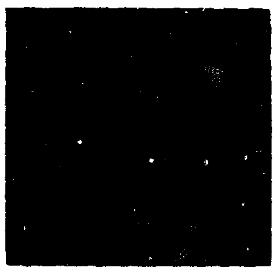
(2) Large Forging Development

The development of Waspaloy in the J58 engine has paralleled the development of Astroloy. Waspaloy, being a much older alloy, was farther along in development when it was specified for use in the J58 engine for major components; but many of the problems that plagued Astroloy were present in Waspaloy. The ingots used for these large forgings were badly segregated, and this segregation carried over into finished parts. The forgings were nonuniform from area to area in a given part, and in the same area from part to part.

The results of the ingot evaluation program on Astroloy have been applied to Waspaloy; as a result, the segregation from poor ingot structure has been virtually eliminated from most suppliers' material.

A J58 forging development program was directed by FRDC metallurgists to forge flat compressor and turbine disks to controlled fine grain uniform parts. This program, completed within a 2 month period, demonstrated that Waspaloy could be forged with a uniform high level of properties and to very tight grain size and microstructural control. Waspaloy disks produced to PWA-1016 must have a grain size of ASTM 4 or finer with occasional grains as large as ASTM 3 allowed; the grain boundary and twin boundary condition when viewed with the electron microscope at 10,000X must not show continuous grain boundary films. (See figure 20.) If more than two percent of a grain boundary has a continuous film, the part is subject to rejection. This specification and the additional microstructural standards imposed on disks yield the highest quality nickel base alloy forgings produced for engine use.

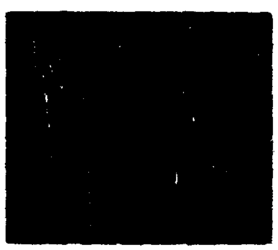
Acceptable Grain and Twin Boundary Carbides



ACCEPTABLE: Unrecrystallized twin containing large particle globular $M_{23}C_6$ carbides.

Rejectable Grain and Twin Boundary Carbides

REJECTABLE: Solidly packed globular $M_{23}C_6$ carbides at unrecrystallized twin plane.



ACCEPTABLE: Larger, heavier concentration of $M_{23}C_6$ carbide particles, but all globular, discrete and dispersed.

REJECTABLE: Grain boundary heavy with precipitation of cellular-shaped $M_{23}C_6$ carbides.

Acceptable Grain and Twin Boundary Carbides

Rejectable Grain and Twin Boundary Carbides

Figure 20. Electron Microscope Standards Used To Review Waspaloy Rotating Hardware Magnification - 10,000X

FD 16585
FII

(3) Sheet Development

Most of the sheet metal in the J58 engine is Waspaloy. Early in the engine history, there was a great deal of trouble with weld and heat treat cracking in Waspaloy assemblies. Loss of properties was also occurring in the manufacturing cycle. These problems were encountered on sheet from all vendors. A development program was established to overcome these problems by furnishing a higher quality sheet and learning more about the response of the alloy to heat treatment and fabrication processes. The first phase of the program was to evaluate the effect of sheet rolling temperatures and reduction schedules on hot rolled material. A flow chart of the mill processing is shown in figure 21. The formability, weldability, resistance to heat treat cracking, mechanical properties, and microstructure were evaluated for each of the eight conditions shown. Seven different solution temperatures (from 1800°F to 2100°F in 50°F increments) were used on each of the eight sheet conditions for the study of heat treat cracking. The results of this testing are shown in figure 22. The weld test specimen configuration was designed for Waspaloy so that the restraint due to welding would cause cracking in over 90 percent of the tests on production material available from our shop. The restraint of this specimen varies inversely with the diameter of an ID weld in an annular ring.

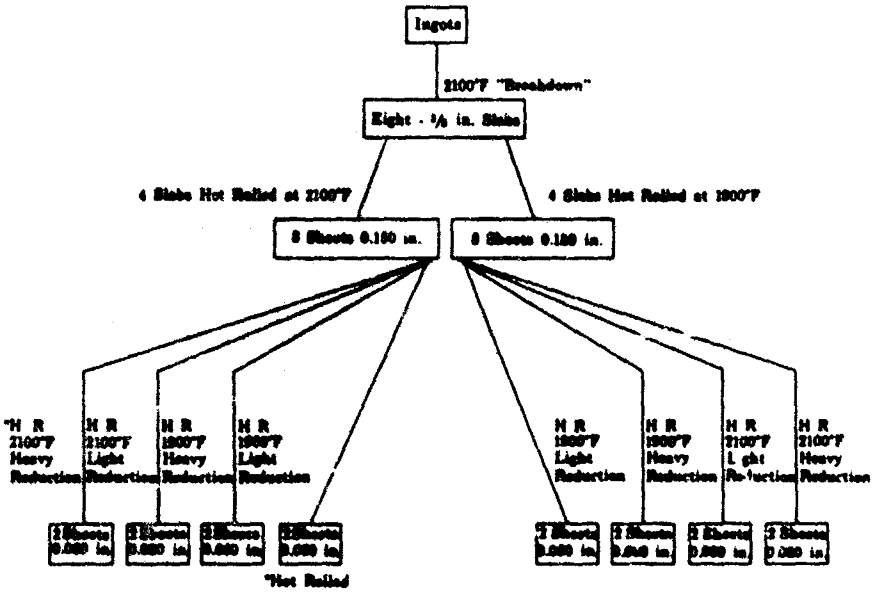


Figure 21. General Flow Sheet of Hot Rolled PWA-1030 Waspaloy Sheet from Ingot to Finished Form

FD 16586
FII

Temperature at Which Sheet was Solutioned Prior to Testing - 1 hr

2100°F	S	F	S	S	S	S	F	F
	S	S	S	F	F	S	S	S
2050°F	S	S	S	S	S	S	S	F
	S	S	S	S	S	S	S	S
2000°F	S	S	S	S	F	S	S	S
	S	S	S	S	F	S	S	S
1950°F	S	S	S	S	S	S	S	S
	S	S	S	S	S	S	S	S
[illegible]0°F	S	F	S	S	S	F	S	S
	S	S	S	S	F	S	S	S
1850°F	S	S	S	S	S	F	S	F
	S	S	S	S	F	F	S	F
1800°F	S	S	S	S	F	F	S	S
	S	S	F	S	F	S	S	S
Rolling Condition	11H	11L	21H	21L	12L	12H	22L	22H

F = Test Failed After Ageing at 1400°F
S = Test Sound After Ageing at 1400°F

Figure 22. Strain Age Cracking as a Function of Hot Rolling History and Solutioning Temperature FD 16588 FII

The results of the hot rolling phase of the program were conclusive. Processing history in hot rolled Waspaloy was reflected in the properties and resistance to heat treat cracking. Final hot rolling temperature was the most influential variable affecting the properties evaluated; intermediate rolling temperature and the percentage reduction were evident in properties, but were secondary to the finishing temperature. The optimum hot rolling conditions established by this program were (1) the use of heavy reduction and (2) low rolling temperatures after the initial ingot breakdown.

The second phase of the Waspaloy sheet development program was the cold rolling portion. The material was forged and hot rolled from the ingot down to 0.375-inch thick sheet bar using high temperature. The sheet bar was hot rolled to 0.100-inch sheet at the optimum temperature of the hot rolling program, 1900°F. From this point on down to 0.060-inch, the material was cold rolled and annealed as shown in the flow chart in figure 23. These were full size sheets of material from a production heat. The sheet produced was cold rolled and annealed, representing eight different practices.

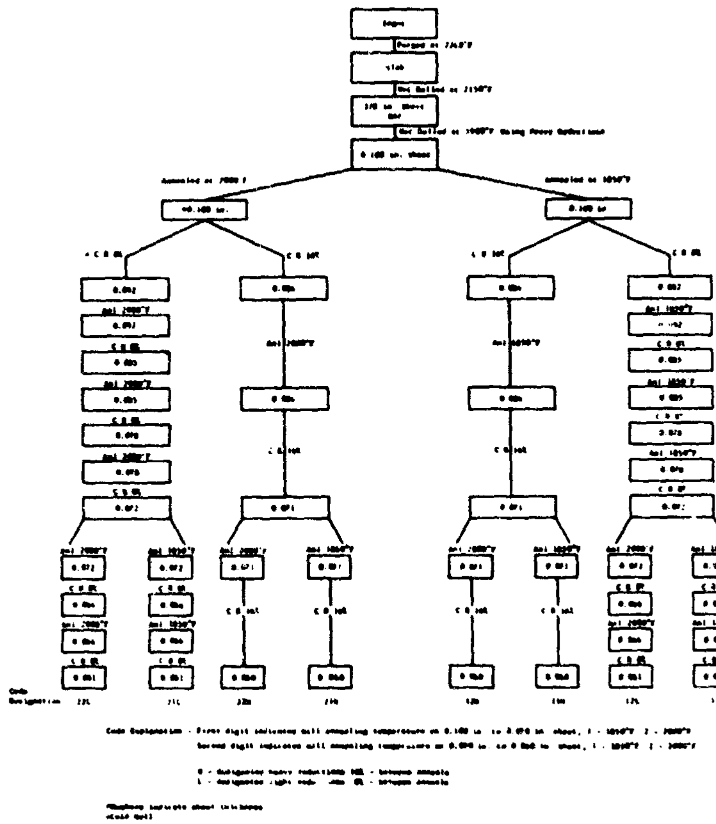


Figure 23. General Flow Sheet of Cold Rolled PWA-1030 Waspaloy Sheet FD 16589

Mechanical properties, formability, hardness, and strain age cracking tendencies were determined for each rolling practice using different solution heat treat temperatures for each practice. The results of the strain age or heat treat cracking tests are shown in figure 24. The material with heavy reduction had better tensile and yield strength and significantly better rupture ductility with a higher hardness, slightly lower formability, and better resistance to strain age cracking.

The overall conclusion from this development effort was (1) high temperature breakdown from the ingot to sheet bar is needed to eliminate segregation and produce a homogeneous product, (2) heavy reductions during both hot and cold rolling operations are needed for optimum properties and resistance to heat treat cracking, and (3) material furnished in the hot rolled condition should be finished, after homogenization, at approximately 1900°F.

Temperature at Which Sheet was Solutioned Prior to Welding T = 20 min

Temperature								
2000°F	S	F	F	F	S	F	S	F
	F	F	F	S	S	F	F	F
1950°F	F	F	F	S	S	F	S	S
	F	S	S	S	S	F	S	S
1900°F	S	F	S	S	S	F	S	S
	S	F	S	F	F	S	S	S
1850°F	F	F	F	F	F	S	S	F
	F	S	S	F	F	S	F	F
1800°F	F	F	F	F	F	F	F	F
	F	F	F	F	F	F	F	F
1750°F	F	F	F	F	F	F	F	F
	F	F	F	F	F	F	F	F
None	S	F	S	F	F	F	F	F
Rolling Condition	11H	11L	21H	21L	12H	12L	22H	22L

F = Test Failed After Ageing at 1400°F
S = Test Sound After Ageing at 1400°F

Figure 24. Strain Age Cracking as a Function of Cold Rolling History and Solutioning Temperature — FD 16590 FII

The results of this development program have led to the production of better Waspaloy sheet for welded assemblies. This is shown by almost complete freedom from weld and heat treat cracking of current sheet material used in the J58 engine.

(4) Bolt Development

Because of the higher temperatures being encountered in the advanced J58 engine, a critical review of Waspaloy bolts was conducted early in 1964. Waspaloy bolts did not have the necessary uniformity or elevated temperature properties for long time operation in this engine. Therefore, an extensive test program was conducted to investigate effects of material structure, grain size, and processing sequence of applying threads and head. Room temperature and elevated temperature tensile, stress rupture, stress relaxation, and fatigue tests were conducted.

These test results enabled P&WA to select the proper structure, grain size, and processing sequence of applying heads and rolling threads to make better Waspaloy bolts than previously manufactured. More important, it enabled P&WA to realize the full potential and limitations of Waspaloy as a high temperature bolting material.

c. PWA-1009, PWA-1010, and PWA-1033

PWA-1009, PWA-1010, PWA-1033 (Inconel 718) was first introduced to the public in 1959. Inconel 718 is an age hardenable nickel base alloy developed for both cryogenic and gas turbine application to 1300°F. The strengthening mechanism used in the alloy is unique in that the material derives its strength from columbium which combines with nickel, aluminum, and titanium to form gamma prime, $Ni_3(Al,Ti,Cb)$, which is coherent with the gamma matrix. The gamma prime reaction and precipitation is quite sliggish in comparison with the conventional $Ni_3(Al,Ti)$ precipitation which occurs in most typical high strength age hardenable nickel base alloys (e.g. Waspaloy). It is from this characteristic that the alloy derives its excellent resistance to heat treat cracking. Inconel 718 is specified for the following components for the JTF17 engine:

1st through 8th Stage Vanes	High Compressor
Exit Guide Vane	High Compressor
5th through 8th Stage Cases	High Compressor
Flanges and Rings	Main Diffuser Case
Sheet Material	Main Diffuser Case
Outer & Inner Cases, Forward	Main Burner
Outer & Inner Cases, Rear	Main Burner
Support Cone	#3 Bearing Support
Front and Rear Housings	#3 Bearing Support
Rear Mount Case	Fan Duct
Intermediate Outer Duct Case	Fan Duct
Inner Access Panel	Fan Duct
Clamshell Pivot, Male	Reverser Suppressor

(1) Background

P&WA became interested in Inconel 718 when it was first learned that the material exhibited good repair weldability, coupled with high strength. An alloy had long been sought that would exhibit good repair weldability and resistance to heat treat cracking and still maintain an acceptable level of strength at intermediate temperatures.

In the 6 years that P&WA has been developing experience with Inconel 718, much technology has been gained and today is manifested in the large quantities of material currently being employed in gas turbine engines.

P&WA applications for Inconel 718 are diversified and range from rotating compressor disks to static complex restrained weldments. Currently, the largest quantities of Inconel 718 are being used in the TF30 and J58 engines and additional sizeable quantities are planned for the new JT9 engine.

(2) Development

In 1960, P&WA embarked upon a comprehensive evaluation program to determine the potential of Inconel 718 for diffuser case applications. In this program, emphasis was directed toward defining the material's strength, long time operating stability, temperature capability, and weldability.

The effects on mechanical properties of different cooling rates from solution and age heat treatments were evaluated. Simulated repair weld and age cycles on restrained weldments were thoroughly investigated. Chemistry modifications involving varying levels of columbium, aluminum, and titanium were also conducted.

Results of the preliminary investigations of Inconel 718 by P&WA were highly encouraging, and the decision was made in 1961 to fabricate two experimental J58 diffuser cases for engine evaluation. Fabrication of these first two diffuser cases, utilizing the results of laboratory investigations, was accomplished with minimum difficulty. Successful fabrication and engine test evaluation of these two diffuser cases was significant for two reasons: (1) it proved that Inconel 718 is an excellent alloy for cases, and (2) the positive results served as an impetus for additional alloy development work directed at blade, vane, and compressor disk applications.

From this early experience, it was determined by P&WA that Inconel 718 is sensitive to processing heat treatment variables. Stress rupture notch ductility, in particular, was found to be sensitive to these variables and, as a result of P&WA direction, subsequent forge and heat treat practices were modified to develop optimum mechanical properties for elevated temperature operation.

The quality of early material was found to be poor. A concerted effort by P&WA metallurgists was made to upgrade quality by giving technology to forging sources; this has resulted in a substantial improvement of the overall quality.

P&WA specifications for Inconel 718 reflect the extensive chemistry modification, heat treat development, and mechanical property development work pioneered by P&WA and serve as a basis for most Inconel 718 specifications utilized by the aircraft industry. This material has been specified for all the production J58 main engine diffuser cases and compressor vanes and cases on the TF30 engine. The knowledge gained by P&WA from its six years of laboratory and engine experience with Inconel 718 is considerable and will result in reliable, high quality engine components for the proposed JTF17 design.

d. PWA-1035

PWA-1035 (TD Nickel) is a relatively new material for high temperature service composed of two volume percent of thoria dispersed in a matrix of nickel. The enhanced properties of PWA-1035 (TD Nickel) are achieved by this chemical dispersion of very minute particles of thorium oxide in the matrix. A uniform dispersion combined with the inherent thermal stability and insolubility of thoria in nickel impart useful mechanical properties to PWA-1035 (TD Nickel) to temperatures in excess of 2000°F. In fact, PWA-1035 (TD Nickel) only becomes competitive with the nickel and cobalt base superalloys in tensile strength and stress rupture properties above approximately 1900°F.

PWA-1035 (TD Nickel) has been specified for components in the JTF17 engine as follows:

1st-Stage Vane	Turbine
Fan Exhaust Nozzle	Duct Burner

(1) Background

Unlike other high temperature materials, PWA-1035 (TD Nickel) does not depend on an exacting thermal cycle to produce dispersed phase strengthening; and the thoria particles are essentially insoluble in nickel at temperatures up to and including the melting point, 2650°F. Uncontrolled temperature excursions will not greatly reduce the mechanical properties of this material. Data available in the literature indicate that exposure to a temperature of 2400°F for 1 hour lowers the room temperature tensile strength only slightly. At higher testing temperatures, the effect becomes even less significant. Other properties such as hardness, average thoria particle size, and average nickel grain size are essentially unchanged after the above thermal exposure.

From the characteristics introduced above, it becomes readily apparent that PWA-1035 (TD Nickel) offers considerable promise for turbine vanes, burner cans, flameholders, and duct burner liners. P&WA has fabricated these components or portions of these from PWA-1035 (TD Nickel) and has obtained considerable experience in J58 engines.

(2) Development

The rolling, forming, and forging of the various listed PWA-1035 (TD Nickel) components have been accomplished with relative ease. Most forming operations are performed at room temperature. Forging may be accomplished at temperatures from 1000°F to 2100°F. The machining techniques applicable to stainless steel are suitable for PWA-1035 (TD Nickel).

Joining by fusion processes causes agglomeration of the thoria dispersoid which results in a considerable loss of strength. Fusion welds with filler material, such as Hastelloy X, yield joints with efficiencies of approximately 80%. Brazing does not disturb the average size or the distribution of the thoria dispersoid; therefore, considerable effort has been expended by P&WA over the past 2 years to develop suitable TD Nickel brazing processes for engine applications. Explosive welding processes have also been developed and widely used to fabricate portions of engine components from PWA-1035 (TD Nickel).

Two methods of accomplishing a resistance braze have been developed by P&WA to a level where reliable joints can be made for engine components such as burner liners. One method involves a shim of a different material between the joint segments of PWA-1035 (TD Nickel). The other method involves producing a high electrical resistance layer on the faying surfaces of the PWA-1035 (TD Nickel) by diffusion processes. Both methods have yielded reproducible and reliable resistance brazed joints which have withstood rigorous engine testing.

Recognizing early in the fabrication development programs the unique peculiarities of the material, mechanical fastening mechanisms have been developed and used in conjunction with resistance brazing and conventional brazing techniques to produce many turbine vane configurations (figure 25).

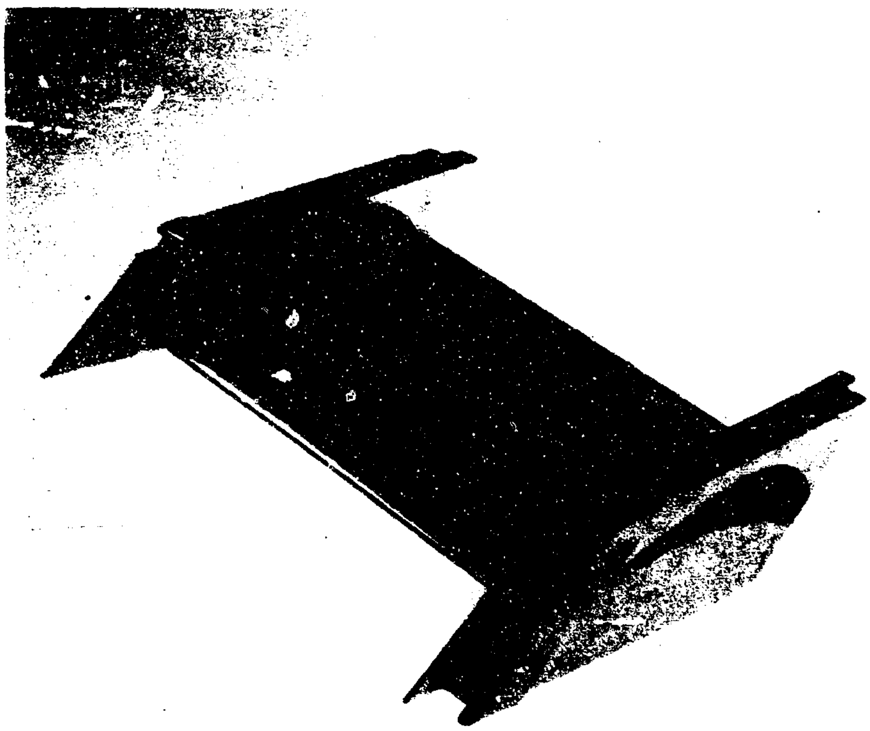


Figure 25. J58 1st-Stage Turbine Vane PWA-1035 (TD Nickel) Airfoil Brazed to PWA-658 (IN-100) Platforms   FE 40395 FII

The experience obtained in these and other fabrication programs has produced experience and confidence in the fabricability of PWA-1035 (TD Nickel) components. P&WA is presently expanding this fabrication experience by developing techniques for joining PWA-1035 (TD Nickel) with castings of other materials that do not rely upon weld or braze joints for strength.

Typical mechanical properties for PWA-1035 (TD Nickel) products have been distributed to the industry by the metal supplier. P&WA has procured and evaluated sufficient quantities of the material to allow the definition of two material specifications. The specifications are PWA-1014 (TD Nickel) for bar and forgings and PWA-1035 (TD Nickel) for sheet and strip. The data obtained from the various lots of purchased material and property development programs have permitted the establishment of design curves for PWA-1035 and PWA-1014 (TD Nickel). An additional program is underway to establish more extensive low cycle fatigue data for PWA-1035 (TD Nickel).

From the time of initial commercial introduction of PWA-1035 (TD Nickel) in 1962, P&WA has been actively engaged in developing fabrication techniques, design data, and engine experience for this material. This experience has shown that PWA-1035 (TD Nickel) can be fabricated with relative ease and offers some very attractive property characteristics in temperature environments in excess of 2000°F. The material is being actively marketed by the producer: it is available in sheet, bars, and forgings in quantities capable of supporting the JTF17 demands.

e. AMS 5536 and AMS 5754

AMS 5536, 5754 (Hastelloy X) is a nickel base non-age hardenable alloy. It has a combination of strength, oxidation resistance, metallurgical stability, and fabricability that is superior to most other non-age hardenable nickel and iron base alloys used in high temperature, low stress applications. It is specified for the following components of the JTF17 engine:

Burner	Main Burner
Transition Duct	Main Burner
Rear Inner Case	Turbine Exhaust
Forward and Rear Inner Duct	Fan Duct
Duct Burner	Duct Heater
Front and Rear Screech Liners	Liners
Intermediate Cooling Liners	Liners
Rear Cooling Liners	Liners
Tail Feathers	Reverser-Suppressor
Clamshells	Reverser-Suppressor

Hastelloy X has been in wide use in jet engines since the mid 1950's and is used in the combustion system of most current engines manufactured in this country. It is relatively inexpensive and readily available in the quantities required for the JTF17 engine.

f. PWA-1003 and AMS 5660

PWA-1003 and AMS 5660 (Incoloy 901) is an austenitic, iron-nickel base precipitation hardened alloy that is used in the following JTF17 components:

Shaft	Fan
Front Hub	Turbine
Spacer	High Compressor

The basic composition for Incoloy 901 was developed by International Nickel Co. but, through the cooperative efforts of a forging source and P&WA, the chemistry, melting, forging, and heat treatment practice were revised to produce an alloy having high tensile properties, good creep rupture life, and ductility with a minimum of notch sensitivity. Creep and stress rupture strength of the alloy are inferior to Waspaloy; forgeability is superior, and costs are much lower. Incoloy 901 is available both in bars and forgings (AMS 5660) and, when higher strength forgings are required, it is available as PWA-1003. PWA-1003 requires higher strength properties than does AMS 5660.

(1) Substantiation

AMS 5660 (Incoloy 901) was first used by P&WA when the upgrading and modifying of the J57 engine to a fan design made it necessary to utilize a higher strength 1st stage disk material than AMS 5735 (A-286), the alloy then being used. Shortly after, when sufficient forging technology had been obtained, PWA-1003 (Incoloy 901) was introduced requiring a higher level of properties than AMS 5660. PWA 1003 (Incoloy 901) is now commonly used in all commercial P&WA engines, primarily for disks, shafts, spacers and tie rods.

3. Proposed Alloys - Advanced Development

a. Astroloy (Sheet)

A high strength sheet alloy with higher temperature capability than Waspaloy has been successfully fabricated from Astroloy sheet and forged rings for an advanced J58 afterburner duct. This part is shown in figure 26. It contains over nine hundred inches of fusion welding in the Astroloy components. P&WA has had an Astroloy welded assembly in engine operation since February of 1966.

Figure 26. J58 Afterburner Duct Fabricated From Astroloy Sheet and Rings FE 59804 FII

The program was started in June of 1964. The design of the duct was changed to allow special welding techniques and a manufacturing sequence that would yield a part essentially free of residual stresses prior to head treatment. Under the direction of P&WA metallurgy, the material processing techniques including melting practice, ingot practice, sheet bar forging technique, and sheet rolling schedule were developed. The sheet and forged rings were received for the start of fabrication in November, 1964. The temporary tooling used on this part caused more weld fit-up variation than desired and some of the joints had to be rewelded. All of the joints were machine welded on semi-automatic equipment using Waspaloy filler wire. All welds were given a stress relief prior to heat treatment. After solution heat treatment there was one small crack in the part which was associated with contamination in the weld bead.

Mechanical properties in welded and heat treated samples were very good. The stress rupture life at 1700°F and under a load of 25,000 psi was in excess of 100 hours with elongation of five percent or more. Waspaloy, one of the better high temperature sheet materials, can withstand only about 11,000 psi for 100 hours rupture life at 1700°F.

Further development by P&WA has led to a substantial reduction in the cost of making Astroloy sheet, as well as improving gage tolerance variation and sheet flatness. Additional parts are scheduled to be fabricated from this improved material during the latter part of 1966.

b. IN 100 and Mar-M200 Modifications

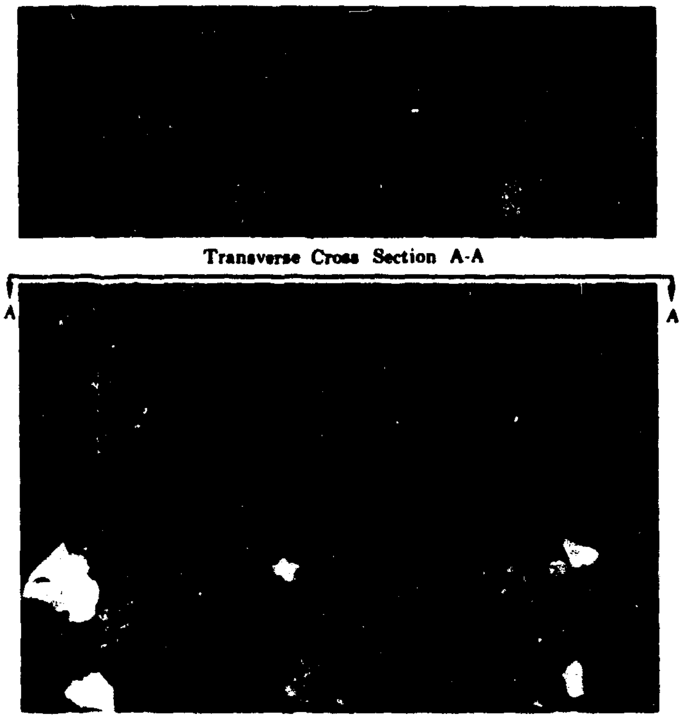
For use in the J58 engine, P&WA metallurgists successfully completed a development program aimed at producing a turbine disk with a minimum of 50°F advantage over PWA 1013E (Astroloy). This disk would provide for higher operating temperatures or extended life. Prior to initiation of this program, unsuccessful attempts had been made by others to forge the highly alloyed nickel base alloys, such as Mar-M200, which were developed for and are presently being used as turbine blade castings. Such alloys, it was reasoned, should afford superior elevated temperature properties to existing forged disk alloys by virtue of their higher hardener content. Based upon the knowledge and techniques gained from the Astroloy development program, it was believed by P&WA that with a good ingot and proper forging procedures these "cast" turbine blade alloys could be successfully forged into crack-free disk configurations. Accomplishing this, it was also believed that through intensive structural evaluation a heat treatment could be developed which would provide the high level of properties being sought with an acceptable level of ductility.

The program was begun with assessment of the basic ingot practice. P&WA found that forgeability of nickel base systems could be significantly improved if the ingot could be processed to eliminate gross segregation. The optimum ingot is one in which compositional changes due to segregation are controlled on a micro rather than macro scale. Therefore, it was reasoned that an ultra-fine grain ingot was required.

Through proper casting controls, an ingot of the desired structure was produced, and segregates were held to microscopic size. Further refinement of the basic process continued until cast grain sizes of uniform ASTM 2-4 were produced on a repetitive basis in small ingots. Figure 27 shows a typical 12-pound, fine grain ingot of IN 100. Several of these ingots have been forged successfully from Mar-M200 and IN 100 composition, and typical examples are shown in figures 28 and 29. After establishing forging parameters (such as reduction, temperature, lubrication, and tooling), the ingot was scaled-up to a 50 pound size. The same successes were achieved with the larger ingot; Figure 28 shows a 12-inch diameter Mar-M200 disk which was forged with a total reduction greater than 85%. An IN 100 disk was forged to a total reduction greater than 90%. Thus far, the maximum size produced has been a five-inch diameter, 100 pound ingot exhibiting a uniform cast grain size of ASTM 4. However, present activity is being coordinated with a material source to produce fine grain ingots weighing 500 pounds of sufficient size for engine turbine disks.

Probably the most difficult problem to overcome in disk forgings was elimination of the previously discussed "die-lock" condition. Figure 30 illustrates "die-lock" resulting from use of conventional operations to produce a small disk in a development alloy. For comparison, figure 30 shows the same composition forged to eliminate "die-lock" and yield maximum uniformity.

Microstructural studies for heat treatment development have been undertaken using disk material from the previously described work to obtain satisfactory properties for advanced turbine disk application. Preliminary tests have been run to correlate microstructure to mechanical properties, and attempts to correct deficiencies have been made by additional heat treat experiments. Mar-M200 has continued to exhibit low ductility at intermediate temperature; overall strength, however, is very encouraging.



Photomicrographs Reduced From 100X

Figure 27. Longitudinal and Transverse Cross Sections of a 12-Pound IN-100 Fine Grain Ingot Showing Uniform, Equiaxed Grain Structure — FD 16591 FII

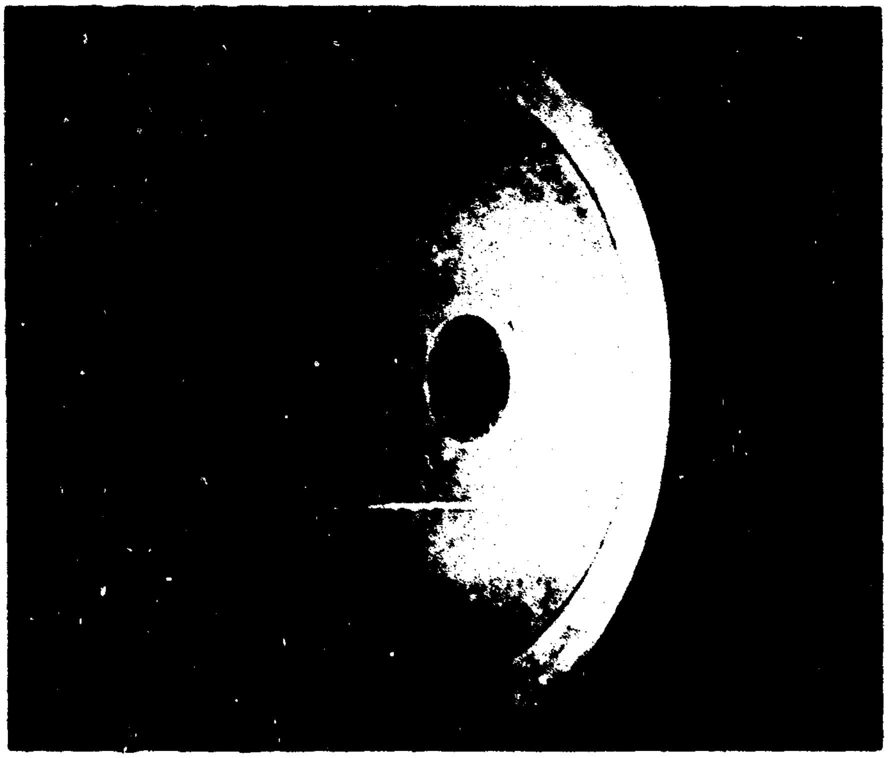


Figure 28. Forged Mar-M200 12-Inch Diameter Experimental Disk — FAL-921 FII

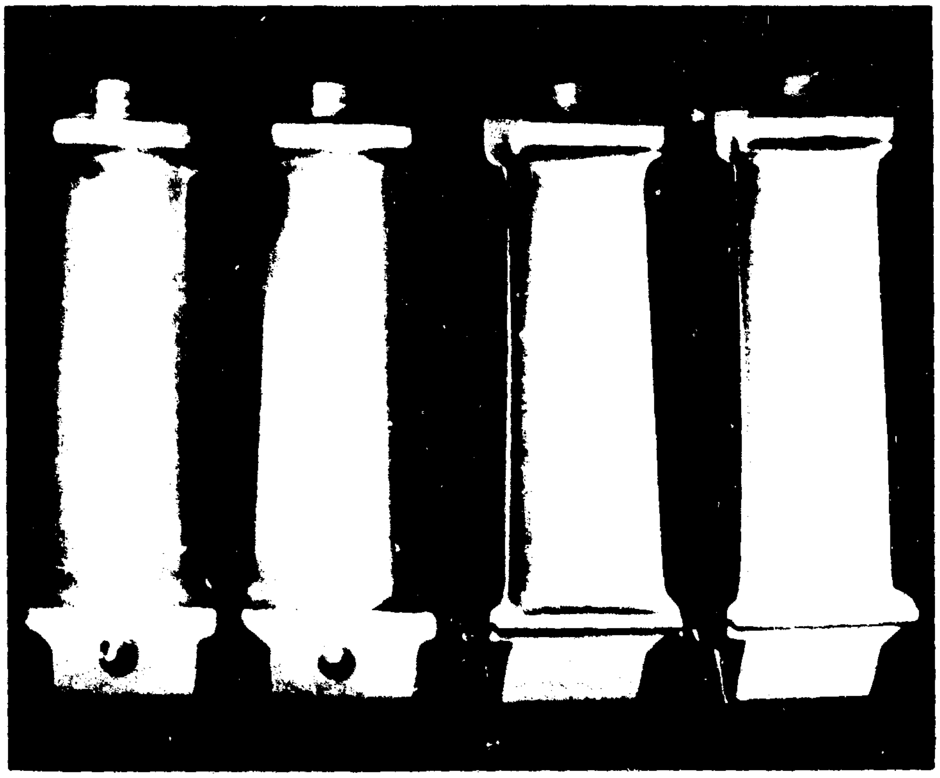


Figure 29. Forged IN-100 JT3D Turbine Blades FAL-9211 FII

Cross Section of Disk Forging Produced by Conventional Techniques Showing Severe "Die Lock"

Cross Section of Disk Forging Produced by Modified Techniques Developed by P & WA Showing Uniform Structure with No Evidence of "Die Lock"

Figure 30. Results of Forging Development Program to Eliminate "Die Lock" and Promote Uniformity in Disk Forgings FD 16594 FII

Chemistry modifications in conjunction with heat treat studies are being conducted to improve the ductility. These include reduction of the tungsten content in Mar-M200 to achieve a more ductile matrix and carbon-boron variations to set up a grain boundary condition for better rupture ductility.

Modifications to the IN 100 composition are being prepared to evaluate the effects of cobalt, carbon, and boron variacions on mechanical properties. A summary of current results are compared to typical PWA-1013E (Astroloy) properties in table 4.

Table 4. Modifications of Mar-M200 and IN 100 Test Results - PWA-1013E (Astroloy) Included for Comparison

Tensile

Alloy	Temp °F	0.2% YS, Ksi	UTS, Ksi	El%	RA%
Mar-M200	RT	156.0	182.8	11.0	8.6
IN 100	RT	149.0	201.5	20.7	19.2
PWA-1013	RT	146.0	202.5	20.0	23.0
Mar-M200	1450	146.6	165.0	2.0	3.9
IN 100	1450	138.9	152.3	9.3	15.6
PWA-1013	1450	122.0	147.0	28.0	42.0

Stress Rupture

Alloy	Temp °F	Stress, Ksi	Life, Hr	El%	RA%
Mar-M200	1450	85.0	43.4	1.9	3.2
IN 100	1450	85.0	42.0	9.5	13.6
PWA-1013	1450	85.0	12.5	22.5	25.0
Mar-M200	1800	29.0	43.6	7.8	6.3
IN 100	1800	29.0	12.0	7.4	7.0
PWA-1013	1800	29.0	7.0	12.5	15.0

Creep

Alloy	Temp °F	Stress, Psi	Time to 0.1% Hr	Min Creep Rate in/in/hr
Mar-M200	1350	74,000	395	2.5×10^{-6}
IN 100	1350	74,000	71	13.3×10^{-6}
Astroloy	1350	74,000	42	21.8×10^{-6}

From the results obtained with these two alloys, it appears at this time that the next generation of forged nickel base superalloys will evolve from this work. Continuing programs are in progress at P&WA to reach this goal.

An adjunct to this disk forging program was an effort to evolve a blade forging with superior properties to the strongest commercially available wrought turbine blade alloy, U-700. The fine grain ingots previously developed were successfully processed into barstock using technology gained from the disc forging work. The barstock was subsequently forged into JT3D turbine blades (figure 29). Using a heat treatment developed from preliminary microstructural investigation, it has been determined that a blade forging alloy superior to U-700 has been developed (figure 31).

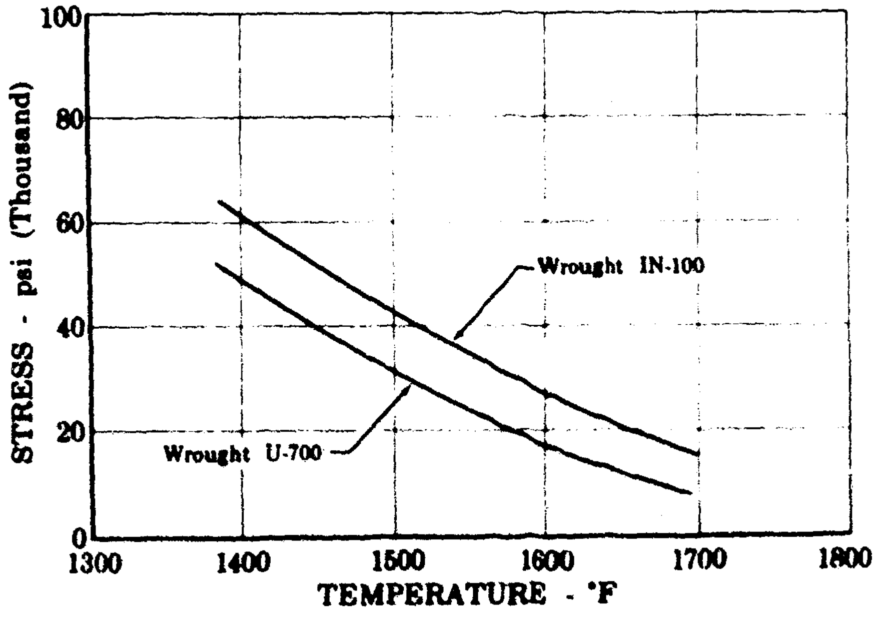


Figure 31. Comparison of 3000-Hour Stress Rupture Life of Wrought Blade Alloys

FD 16592
FII

Using the casting and forging technology that was used in producing the IN 100 barstock, barstock has been produced from a modified Mar-M200 composition to obtain even greater high temperature strength. With a heat treatment developed from a short run microstructural evaluation, very preliminary data obtained indicates high temperature strength potential comparable to cast PWA-664 (figure 32). Since the 3rd-stage turbine blade is a solid blade, this modified

Mar-M200 conposition can be considered as a forging backup for the specified casting if any unexpected difficulties should arise in the production of this part.

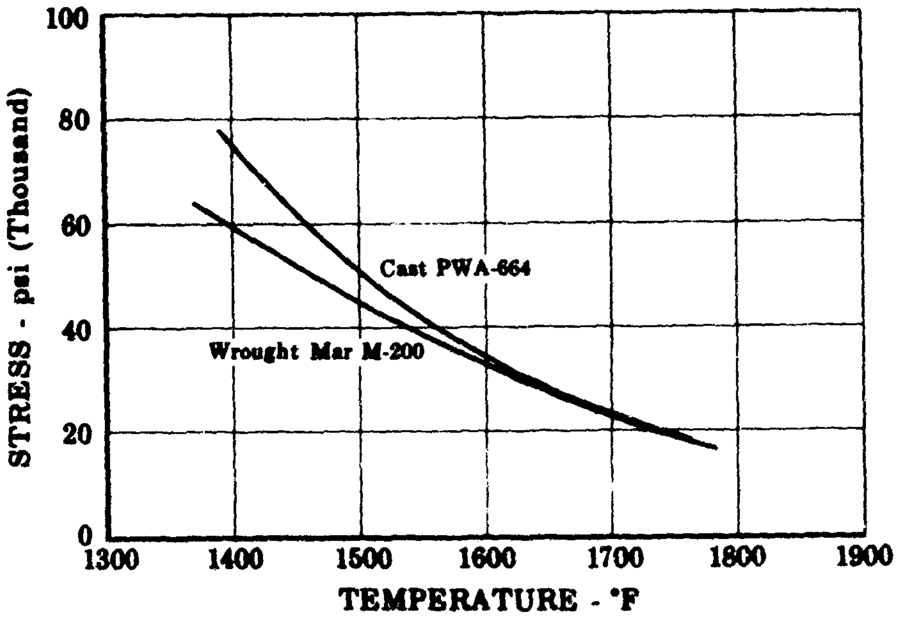


Figure 32. Comparison of 3000-Hour Stress Rupture Life of Wrought Mar M-200 and Cast PWA-664 — FD 16593 FII

c. UX-1500

Wrought alloy development no longer need be held below certain hardener limits as now defined by the bulk of the technical metallurgical literature. Improved fine grain ingot practice and forging techniques have allowed this significant advance.

With the fine grain ingot paving the way, radical modifications of the Astroloy composition were developed, and in late 1964 a metal producer introduced a high titanium Astroloy system, designated UX-1500. Original testing by P&WA showed a pronounced strength advantage over the nominal Astroloy composition, especially in creep strength. These improvements are underlined in table 5.

Table 5. Comparison of Creep and Stress Rupture Properties of UX-1500 and Astroloy

Creep Resistance

	Temp, °F	Stress, Psi	Time to 0.1%, Hours
Astroloy	1300	74,000	165
UX-1500	1300	74,000	890

Stress Rupture

	Temp °F	Stress, Psi	Life, Hr	El, %
Astroloy	1400	85,000	40	18.0
UX-1500	1400	85,000	198	9.3

However, during the course of testing, several limitations inherent to the composition were uncovered. Notably, the balance between alloying elements was incorrect which resulted in a massive phase detrimental to tensile ductility.

Based on correlations between structure, heat treat response, and mechanical properties, the metal producer was directed to produce further aluminum-titanium modifications to the base composition in order to establish an optimum chemical balance, while simultaneously insuring that a suitable total aluminum plus titanium content was maintained. A concurrent effort by P&WA to define the heat treating characteristics was undertaken in order to produce a heat treating cycle capable of utilizing the alloy's full potential.

Using creep-rupture life as the prime index, numerous compositions of varying aluminum-titanium ratios as well as total hardener content were prepared. Figure 33 summarizes the results. For this work, identical conversion processes and heat treatments were used for all heats to ensure validity of the data solely as a function of aluminum and titanium content.

The original composition evaluated by P&WA appears at the point "A" of figure 33; the composition finally selected by P&WA appears at the point "B". The composition does not fall directly within the region

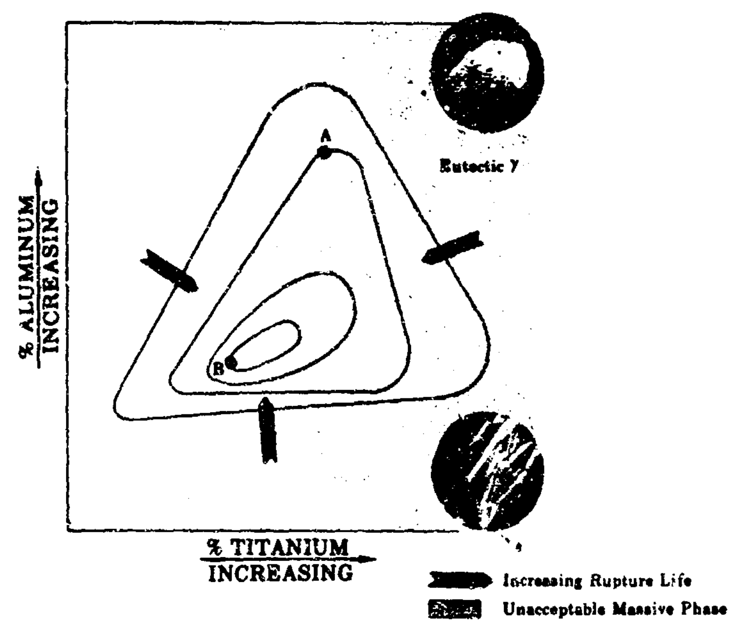
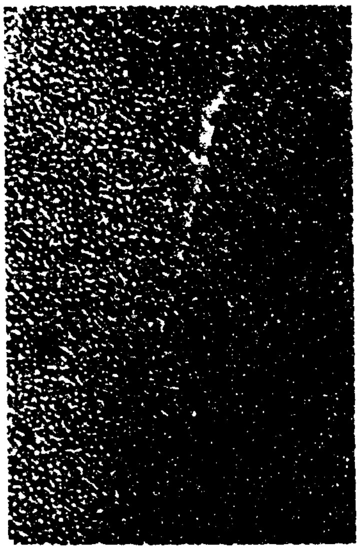


Figure 33. Creep-Rupture Life of UX-1500 as a Function of Aluminum and Titanium — FD 16595 FII

of maximum rupture life because of a desire to minimize effects of a massive phase which could not be taken into solution. As shown in figure 33 high aluminum levels produced a brittle eutectic gamma prime phase and high titanium-aluminum ratios a brittle eta phase. The final composition point "B" is one in which the presence of these phases has been minimized with only a small decrease in strength.

Initial heat treatments used to evaluate mechanical properties were based upon utilization of a full solution heat treatment followed by a series of aging cycles to achieve the maximum aging effect. Results from test specimens heat treated in this manner showed the desired 50°F advantage over Astroloy had been achieved but that both tensile and rupture ductility would have to be improved for disk applications.

Observations of broken test specimens show failure at both room and elevated temperature to occur predominantly through the grain boundaries. Studies of these same specimens by electron microscopy show that within the grain boundaries a continuous gamma prime film exists in which the secondary carbides are enveloped, as shown in figure 34.



Initial Structural Condition Showing γ' Film in Grain Boundary

Optimized Structural Condition Showing Elimination of γ' Film

Figure 34. Electron Microscope Comparison of UX-1500 Structures — FD 16596 FII

In considering the nature of the gamma prime precipitate, it was reasoned that for high titanium to aluminum ratios a maximum substitution of titanium for aluminum was being approached. In this case, the strengthening of the alloy is attributed not only to a greater lattice straining but also to a strengthening of the gamma prime itself. Unfortunately, strengthening also decreased the ability of the gamma prime to deform. Thus, if such a gamma prime film (actually a grain boundary envelope) existed in a continuous nature throughout the grain boundaries, a brittle type fracture would always occur. The filming effect had to be eliminated in order to produce acceptable ductility. Subsequent thermal studies showed that the filming effect was attributed to chromium depletion during the formation of secondary $M_{23}C_6$ type carbides. Additional thermal treatments were incorporated to suppress the grain boundary carbide-gamma prime interaction.

When the proper solution heat treating and stabilizing sequence was established, the required tensile and rupture ductility were obtained; when combined with a final two stage aging cycle, the desired strength levels also resulted. The resulting structure is shown in figure 34.

After final optimization of the times and temperatures involved in the overall heat treating process, the following property levels had been achieved and sustained on a repetitive basis. Typical Astroloy data are included in table 6 for comparison.

Table 6. Comparison of Mechanical Properties of UX-1500 and Astroloy

Tensile

	Temp, °F	0.2% YS, psi	UTS, psi	El%	RA%
UX-1500	RT	148,000	212,000	12.0	13.5
Astroloy	RT	146,000	202,500	20.0	23.0
UX-1500	1450	130,000	152,600	15.0	18.0
Astroloy	1450	122,000	147,000	28.0	42.0

Creep Rupture

	Temp, °F	Stress, psi	Life, hr	El%	RA%
UX-1500	1450	85,000	33.0	14.0	16.0
			Notch life greater than 300 hours		
Astroloy	1450	85,000	12.5	22.5	25.0

Creep

	Temp, °F	Stress, psi	Time to 0.1%, hr
UX-1500	1350	74,000	170.0
Astroloy	1350	74,000	42.0

Room Temperature Tensile Properties After Creep Testing (Stability):

	0.2% YS, psi	UTS, psi	El, %	RA, %
UX-1500	156,000	210,000	10.0	10.0
Astroloy	153,000	209,000	17.5	19.5

Present work is now directed toward producing a full-scale UX-1500 J58 turbine disk forging for property evaluation. With success in this area, as is now assured, engine tests will be scheduled for the final evaluation.

d. PWA-1040 (Inconel 625)

There exist numerous instances where, because of a specific parts operating temperature or temperature range, it is desirable to use a non-age hardenable material. An age hardenable alloy that is required to operate in its ageing range is prone to metallurgical instabilities and unacceptable mechanical properties. Significant development effort has been directed towards non-ageing alloys possessing higher strength, better weldability, and less susceptibility to embrittlement during long time operation for use in combustion systems.

PWA-1040 (Inconel 625) is a relatively new non-age hardenable nickel base alloy. Initial investigation and testing performed by P&WA in 1964 indicated that the alloy possessed substantially higher tensile properties than current non-age hardenable nickel base alloys (i.e. Inconel 600, Hastelloy X, Hastelloy N). The improved capabilities of PWA-1040 (Inconel 625) are obtained through solid solution strengthening using additions of molybdenum and columbium. International Nickel will guarantee a level of properties, on material annealed at 1800°F, which gives a design advantage of 8000 to 10,000 psi in yield strength over Hastelloy X up to 1400°F, an increase of 20 percent. More recent testing by Battelle Memorial Institute, International Nickel Company, and P&WA shows that PWA-1040 (Inconel 625) annealed at 2100°F possesses strength equivalent to PWA-1035 (Hastelloy X) from 1500°F to 2000°F. This is significant since the material exhibits superior ductility and resistance to time-temperature embrittlement than Hastelloy X. Weldability and formability are excellent. P&WA is currently conducting a comprehensive test program to establish the long time characteristics of the alloy. This testing includes creep rupture, stability after exposure, and oxidation-erosion resistance. If the results of this program are favorable, it is planned to make extensive use of the alloy in the JTF17 engines for liners on reverser-suppressor components.

e. Nickel-Molybdenum-Aluminum System

In 1965, P&WA under sponsorship of the J58 program initiated a development program with a unique ternary alloy system of nickel, molybdenum, and aluminum. The initial property results obtained from investment cast test specimens were so encouraging that additional chemical compositions in the system were investigated. From the examination of the various compositions, a specific composition was chosen for a sheet development program.

The basic objective of the sheet development program was to produce a sheet with tensile properties exceeding those exhibited by AMS 5536 (Hastelloy X) at temperatures above 2000°F. Such a sheet alloy would be primarily for use as combustion chamber components and liners where high temperature strength and oxidation resistance are of primary importance.

The data obtained from the investment cast test specimens indicated that the material would be difficult to roll into sheet. Therefore, a contract was arranged with one of the leading specialty sheet material rolling sources to produce a developmental order of sheet from fine grained ingots which had been procured by P&WA. Hot twist tests performed by the contractor to determine the relative ease of rolling indicated that the material could not be rolled. The first attempt to roll the material seemed to substantiate the results of the hot twist tests as the ingots were badly cracked.

The remnants of the ingots of the first attempted rolling were returned to P&WA for conditioning. They were "canned" and returned to the contractor's facility for a second attempt. Under the direction of P&WA a portion of the available material was rolled into strip three inches wide by 0.060-inch thick. Rolling into strip, though not an easy task, now has also been accomplished by a second rolling source. The experience gained in the rolling evaluations indicates that the material can be rolled on a commercial basis.

Test data have now substantiated that the as-rolled material displays exceptional strength properties. However, heat treat investigations have shown that the material properties can be altered by exposure to temperatures above the rolling temperature. P&WA is presently engaged in a program to improve the fabrication schedule and develop a heat treatment for the best compromise of strength and ductility.

The property data, which are based on limited test results of the material rolled in this sheet program, are compared with the corresponding typical reported property values of Hastelloy X in the attached table 7.

f. PDRL 160

Requirements currently exist for a wrought ultra high strength, nickel base, age hardenable alloy suitable for supersonic compressor applications. Advanced compressor materials that exhibit ultra high strength, good notch ductility and good low cycle fatigue properties are required. Titanium alloys being specified for these applications have temperature limitations near 900°F. Past experience with columbium strengthened nickel base compositions has shown that they have excellent potential for meeting these requirements.

A metal producer has recently made available an experimental alloy of this class designated as PDRL 160 which shows promise. Preliminary data obtained on this alloy indicate that it is equivalent to PWA-1202 (Ti-8Al-1Mo-1V) on a strength-to-weight basis at all temperatures down to room temperature and is, of course, superior to Inco 718 and Waspaloy on a strength basis up to at least 1100°F. P&WA has initiated a program to (1) evaluate PDRL 160 for compatibility with the requirements of high performance supersonic compressor disks, (2) develop weldability and repair weldability characteristics of sheet to determine its suitability for case applications and, (3) provide a basis for chemistry modification to afford temperature capability approaching that of Waspaloy up to 1300°F.

g. Superalloy Powder Processing

The large P&WA ingot development effort that has been described in detail has been devoted to the minimization of segregation through proper solidification of superalloys. Work done to improve the PWA-1013E (Astroloy) ingot by decreasing segregation is discussed in Section II, paragraph D2a(2)(b), which follows the development up to

Table 7. Properties of Nickel-Molybdenum-Aluminum Compared to Hastelloy X

Tensile Properties		Hastelloy X	Ni-Mo-Al As-Rolled	Ni-Mo-Al Heat Treated
Room Temp.	UTS, psi	114,000	212,000	195,000
	YS, psi	52,000	1[illegible]5,000	151,000
	EL	43%	7%	6%
2000°F				
	UTS, psi	13,000	33,000	60,000
	YS, psi	8,000	25,000	52,000
	EL	40%	70%	3%
2200°F				
	UTS, psi	5,400	14,000	16,000
	YS, psi	3,700	11,000	11,000
	EL	31%	75%	10%
Stress Rupture Properties				
2000°F/3000 psi		8 hr	6.5 hr	67.5 hr
1800°F/8000 psi		10 hr	16.7 hr	116.1 hr

present production capabilities of large consumable ingots for Astroloy. The same procedure is now used for Waspaloy and Inconel 718. Further, as-cast grain sizes of ASTM 1 or finer have been achieved on static cast ingots of IN 100 and Mar-M200; the development of this process is discussed in Section II, paragraph D3b.

P&WA believes that this work on consumable and static-cast ingots will exploit all of the potential that is feasible for minimizing segregation in full-scale ingots of superalloys through proper control of solidification. The only remaining opportunity to further minimize segregation in these materials now lies in the area of powder metallurgy. In fact, there is considerable reason for expecting that the gains to be made by using a powder product will be greater than all previous gains combined. It is almost inconceivable that an ingot of the size required for large forgings can be produced by the most sophisticated casting techniques and mold designs that can approach a powder product in homogeniety. Since segregation is caused by thermal gradients occurring during metal freezing, a small powder particle a few microns in diameter will be vastly more uniform in composition than an equal volume of a conventionally cast ingot.

Some very preliminary work performed by a forging vendor has demonstrated that a powder product of Astroloy does, in fact, possess a higher level of properties than that which has been obtained on the best Astroloy forgings from conventional material.

It is recognized that previous powder metallurgy work on superalloys, as well as other materials, has been severely plagued by lack of reproducibility, which can be attributed in large part to incomplete fusion of the individual powder particles. P&WA, however, has evolved a basic concept of producing full-scale billets from powder for large superalloy forgings which is unique. A development program has been initiated to exploit this concept using subscale forging multiples. If the concept proves to be sound, it can be applied to all grades of alloys for exploiting their inherent property capability, which is invariably crippled by segregation attendant to conventional ingot practice.

E. LCF (LOW CYCLE FATIGUE) CONSIDERATIONS FOR COMPRESSOR AND TURBINE DISKS

1. Introduction

P&WA has long recognized the importance of low cycle fatigue in the design of disks for long-time, successful operation in commercial as well as military engines. An extensive and sustained effort has been exerted over the years in which LCF evaluation has taken many forms. Laboratory evaluation has included cyclic combined-stress push-pull testing, cyclic combined-stress flexural testing, and cyclic tension and rupture testing on specimens machined from disks. Additionally full-scale disks have been LCF tested on "Ferris Wheel" rigs (figure 35). Finally, full-scale disks have been spun under cyclic conditions in spin pit facilities. From these various forms of tests, data have been obtained for deriving relationships which have been used for design purposes to ensure LCF capability in compressor and turbine disks.

2. Nickel Base Alloys

Prior to the development of the J58 engine, the magnitude of stresses and temperatures to which compressor and turbine disks were subjected allowed use of less sensitive alloys than Waspaloy and Astroloy. The very stringent temperature and stress requirements of the J58 engine

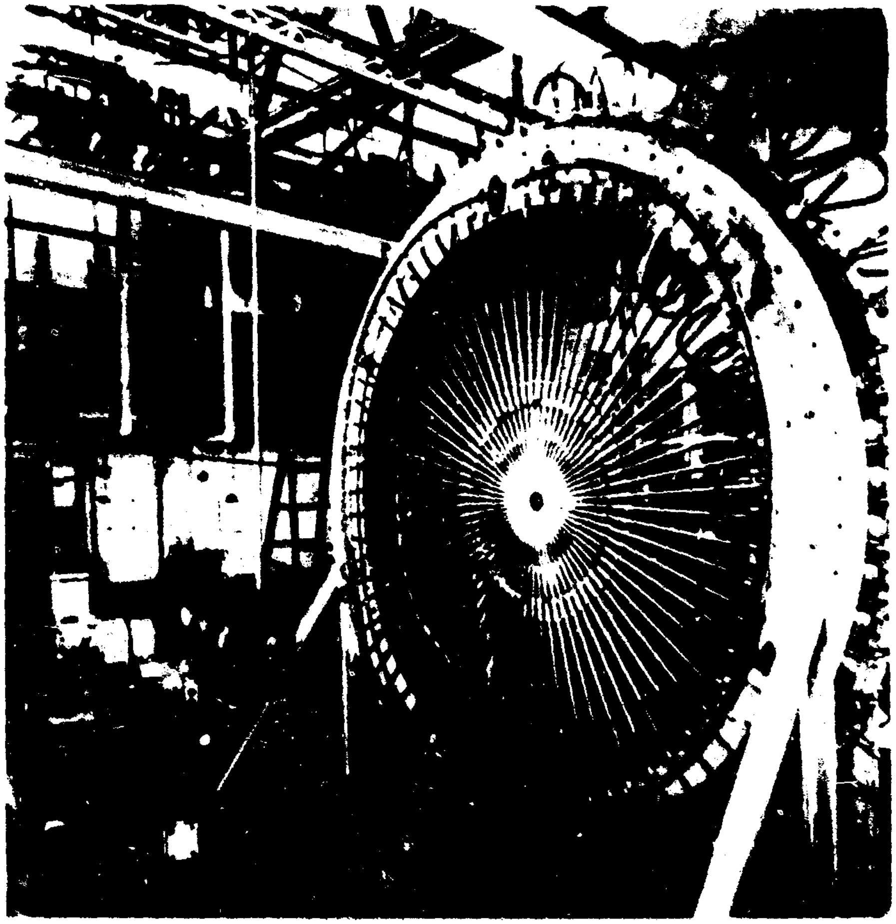
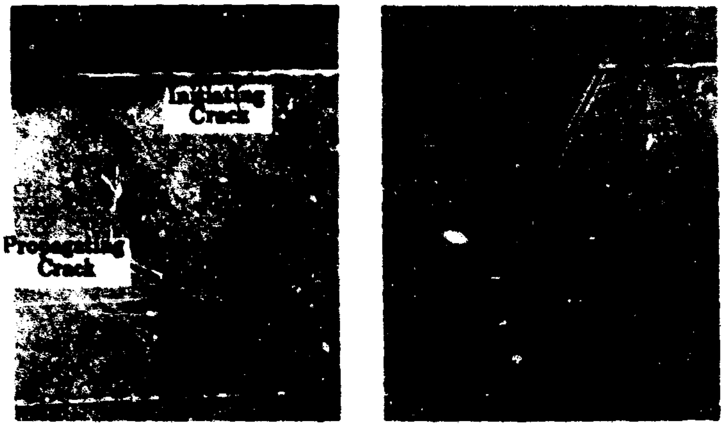


Figure 35. "Ferris Wheel" Test Rig Capable of Cycling Compressor and Turbine Disks Through Stress Ranges Encountered During Engine Operation H-15495A FII

make the use of the latter two alloys mandatory. Further, in case of the J58 and JTF17 engines, it is extremely important to recognize that the stress and temperature conditions to which Waspaloy and Astroloy are subjected are more severe in relation to the inherent strength capability of these alloys than has been the case with disk alloys used in earlier P&WA engines. J58 engine operation and laboratory investigation of Waspaloy and Astroloy disks have established the fact that a correlation exists between microstructure and the LCF properties of these materials.

Cyclic failures have been produced in J58 experimental engine disks of Waspaloy and Astroloy, and, in every case, failure has initiated in coarse grained areas. Fine grained areas are much more resistant to crack initiation. That a fine grained structure would have better fatigue strength than a coarse grained structure is to be expected. However, cyclic failure is more related to the form and packing density of secondary carbides in grain boundaries and twin boundaries. Cyclically induced cracks appear to initiate and definitely do propagate along solid carbide films which are almost invariably found in the grain boundaries of coarse grained structure (figure 36). In discrete, discontinuous carbides usually associated with fine grained structures (figure 34), no cyclic cracking propensity has been observed.



Light Microscope - Initiating and Propagating Cracks Through Grain Boundaries Containing Continuous Carbide Films Magnification 100X

Electron Microscope - Grain Boundary Containing a Continuous Carbide Film (Arrow) Magnification 10,000X

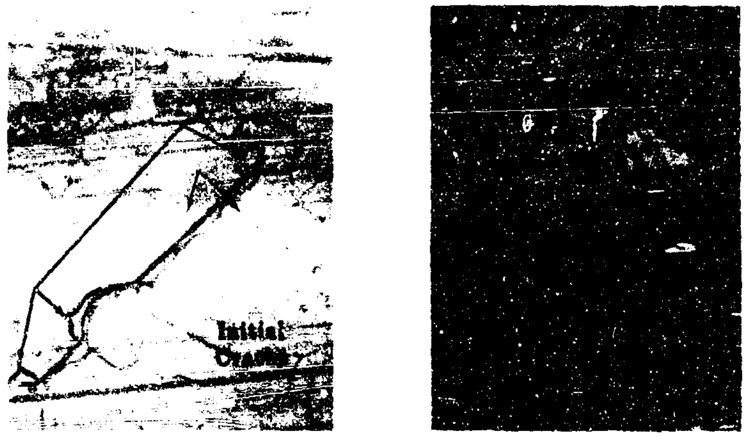
Figure 36. Cyclically Induced Cracks Initiating and Propagating Through Grain Boundaries Containing Continuous Carbide Films — FD 16597 FII

One case in point, which demonstrated the difference in tolerance of the two types of structures to cyclic failure, involved a Waspaloy compressor stage in J58 experimental engines in which several disks were found, after a certain amount of disk growth, to have a multitude of tiny cracks extending circumferentially around the disk in the web between the spacer and the rim. On the basis of engine operating data and stress analysis information obtained by selectively cutting the disks, it was determined that these disks had cracked as a result of thermal cycling associated with aircraft and engine accelerations and decelerations. These disks all had coarse grains in the area of cracks and the cracks themselves were located in continuous carbide films found in twin boundaries and grain boundaries (figure 37). After examining these disks, another disk was examined which had experienced the same type of engine operation and growth but had no cracks. The structure was found to be fine grained with discrete grain boundary carbide particles.

Electron Microscope
Twin Boundaries Containing
Continuous Carbide Films (Arrows)
Magnification 10000X

Figure 37. Cyclically Induced Cracks Through Twin Boundaries Containing Continuous Carbide Films — FD 16598 FII

As a result of the interdependence of microstructure and LCF resistance, P&WA undertook an extensive study on disks. In the past 2 years, the structure of over two hundred Waspaloy and Astroloy compressor and turbine disks of the J58 engine have been critically examined using light and electron microscopes. The examination has been made to determine the form, the extent, and the packing density of secondary carbides in grain and twin boundaries, the relationship of carbide morphology to grain size, the dependence of carbide morphology and grain size on disk processing, and the influence of the various structures observed on engine operation. (Disks examined were in five categories, viz. experimental engines before and after test, production engines before and after operation, and various laboratory-sectioned disks). An engine test was conducted specifically to determine the effect of cycling on the propagation of cracks previously caused by the thermal cycling of a coarse grained Waspaloy compressor disk. (See figure 38.)



LIGHT MICROSCOPE - Picture of Cracks Initiated by Thermal Cycling of Engine Magnification 100X

LIGHT MICROSCOPE-Picture of Cracked Area After Two Additional Engine Cycles Magnification 100X

Note Displacement of Machining Marks Across Crack

Figure 38. Effect of Continued Engine Cycling on the Propagation of Cracks Previously Initiated by Cycling of a Coarse Grained Waspaloy Compressor Disk — FD 16599

As a result of this program, a very stringent grain size requirement of predominately ASTM 4 or finer with occasional grains as large as ASTM 3 has been applied to PWA-1013 (Astroloy) and PWA 1016 (Waspaloy). Grain size is checked at 16 points on each disk produced to these specifications. Four checks are made on the face of the bore, 90 degrees apart on one side of the disk and the same points offset 45 degrees on the other side. The rim is checked in the same manner. If any of the areas checked exceed the grain size requirements of the specification, the coarsest grained area must be replicated and examined on the electron microscope. If continuous grain boundary or twin boundary films of carbide are present, the disk is rejected. Electron microstructural standards for acceptable or rejectable disk microstructure supplement the specifications. (See figure 20.)

These standards for disk acceptance have been established to ensure that Waspaloy and Astroloy disks for the J58 engine have the greatest possible LCF resistance. These same standards have been applied to JTF17 compressor and turbine disks.

3. Titanium Alloys

A great deal of laboratory evaluation has been performed to determine LCF behavior of the various titanium alloys. Design based upon data generated has been highly satisfactory in titanium compressor disks for long life commercial P&WA engines. As indicated in the introduction of this section, work has been initiated to determine the sensitivity of structure to LCF for more demanding requirements, and information gathered will be incorporated into our designs in the future.

4. Continuing Laboratory LCF Evaluation

More definitive LCF information on candidate materials is required, representing a broader sweep of the multiplicity of variables involved than is presently available. Accordingly, an extensive program of laboratory LCF evaluation has been initiated. In the area of disk specimen testing, the program consists of, 1) the generation of design data involving the interaction between LCF and creep-rupture damage and, 2) metallurgical investigation of the effects of structure on LCF behavior and study of modes of failure. In the case of design data generation, testing will include smooth specimens at constant total strain with dwell time (to determine LCF-creep rupture interaction) plus smooth and notched specimens of various stress concentrations at constant load. This program involves a large number of specimens run under a variety of conditions which will collectively represent the broadest spectrum of operating conditions to which disks will be subjected in the engine. This will be done as a part of the Phase III program.

The fracture modes of these specimens are being examined using light and electron fractography for the acquisition of metallurgical information. In addition, a file of fractographs is being maintained of all specimen failures in order that the mode of failure of any disks that might fail during the development of the JTF17 may be more readily identified for corrective action.

In conjunction with this program, correlation tests more closely simulating engine conditions will be run as appropriate on full scale disks, utilizing ferris wheel rigs, including a new one now under construction which will have cyclic temperature capability, as well as spin pit facilities.

F. CAST NICKEL BASE ALLOYS

1. Specified Alloys

a. PWA 658 Blades

First Stage Turbine Blade	PWA-658
Second Stage Turbine Blade	PWA-658
Third Stage Turbine Blade	PWA-658

(1) Evolution of PWA-658 (IN 100) Blade Development

To provide the necessary perspective for considering the specifying of PWA 658 for the 1st, 2nd, and 3rd stage blades for the JTF17 engine, it is appropriate to briefly review cast blade development history.

In 1958, P&WA recognized the necessity for utilizing cast nickel base superalloys for turbine blades to meet the performance goals established for high mach number turbine engines. This requirement made it mandatory that a major development effort involving fundamental, nonconventional approaches be undertaken to obtain blade castings with the desired level of mechanical properties and reproducibility of properties equaling or exceeding that of blade forgings. This development effort, which is still underway today at the Florida Research and Development Center, had led to the successful operation of precision cast turbine blades and vanes in the J58 engine and the results of this work will be utilized continuously in the JTF17 Phase III program.

Commencing in 1962, it was evident that the strongest of the nickel base alloys, PWA-659 (Mar-M200), was not suitable for operation in the J58 engine. It possessed insufficient ductility for crack-free operation of root attachments in the intermediate temperature range. In addition to this deficiency, "state-of-the-art" 1st- and 2nd-stage blade castings being supplied for this engine had a wide variation in grain size and shape, resulting in such a broad scatter of mechanical properties that reliability was of a low order and, therefore, unacceptable. (See figure 39.) In order to rectify this situation, it was necessary that another alloy possessing adequate intermediate temperature ductility as well as strength at elevated temperature be selected. Of equal importance was the need for developing a casting technique which would afford a controlled uniform and equiaxed grain structure throughout, conferring isotropy to the material for desired reliability. Development work aimed toward a controlled equiaxed grain casting technique was initiated. After establishing that controlled structures could be produced in the J58 turbine blade configurations, the supplier and P&WA worked jointly on a process aimed at providing the desired equiaxed grain size with a high degree of soundness which would meet projected requirements. Such a process was successfully evolved and was designated as Grain X. (See Figure 40.) At the same time this casting development was proceeding, an intensive investigation was underway to select an adequate alloy composition. From this investigation, it became apparent that PWA-658 (IN 100) possessed the order of intermediate temperature ductility required.

The main deterrent to the selection of IN 100, however, was its widely rumored tendency toward signa phase formation as a function of temperature and stress exposure after extended lengths of time which, reportedly, was detrimental to mechanical properties. Accordingly, a thorough investigation of "sigma phase scare" was made in conjunction with International Nickel Company, originators of the alloy, and as a result, a composition modification was made to IN 100 by P&WA to reduce the tendency of the alloy to form "sigma". Concurrent with this change, a thorough microstructure investigation involving the morphology and the effects of phases as a function of chemistry, cooling rate during casting, and solutioning and precipitation heat treatments was carried out by P&WA from which a heat treatment was established. This heat treatment afforded a high level of mechanical properties and structural stability, not present in "as cast" material of the "old" IN 100 chemistry. Within less than 1 year from the inception of the program, processes had been established which yielded the desired product.

Following the development of the desired casting processes for each of the two blade configurations, the selection of an improved chemistry, and a highly beneficial heat treatment, P&WA initiated an investigation with the casting supplier to set up a system of stringent process controls. This action was taken to insure reproducible product. After a period of intensive study, extremely tight limits of variation were established for 128 separate operating functions comprising the casting processes which were considered to be most critical in determining the level of properties and integrity of the finished part.

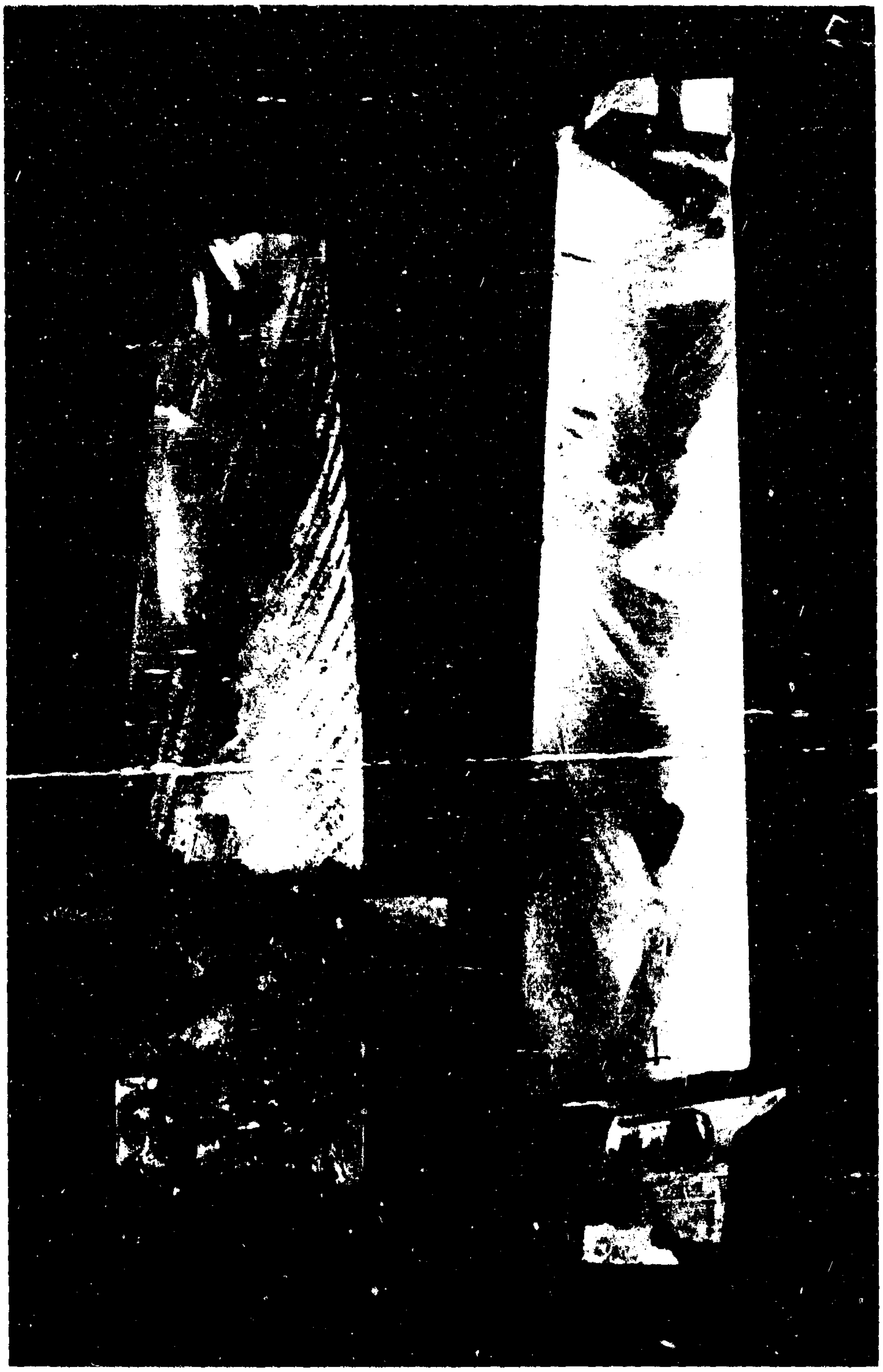


Figure 39. J58 Turbine Blades Showing Extreme Variations in Structure and Grain Size PWA-659 (MAR-M200)

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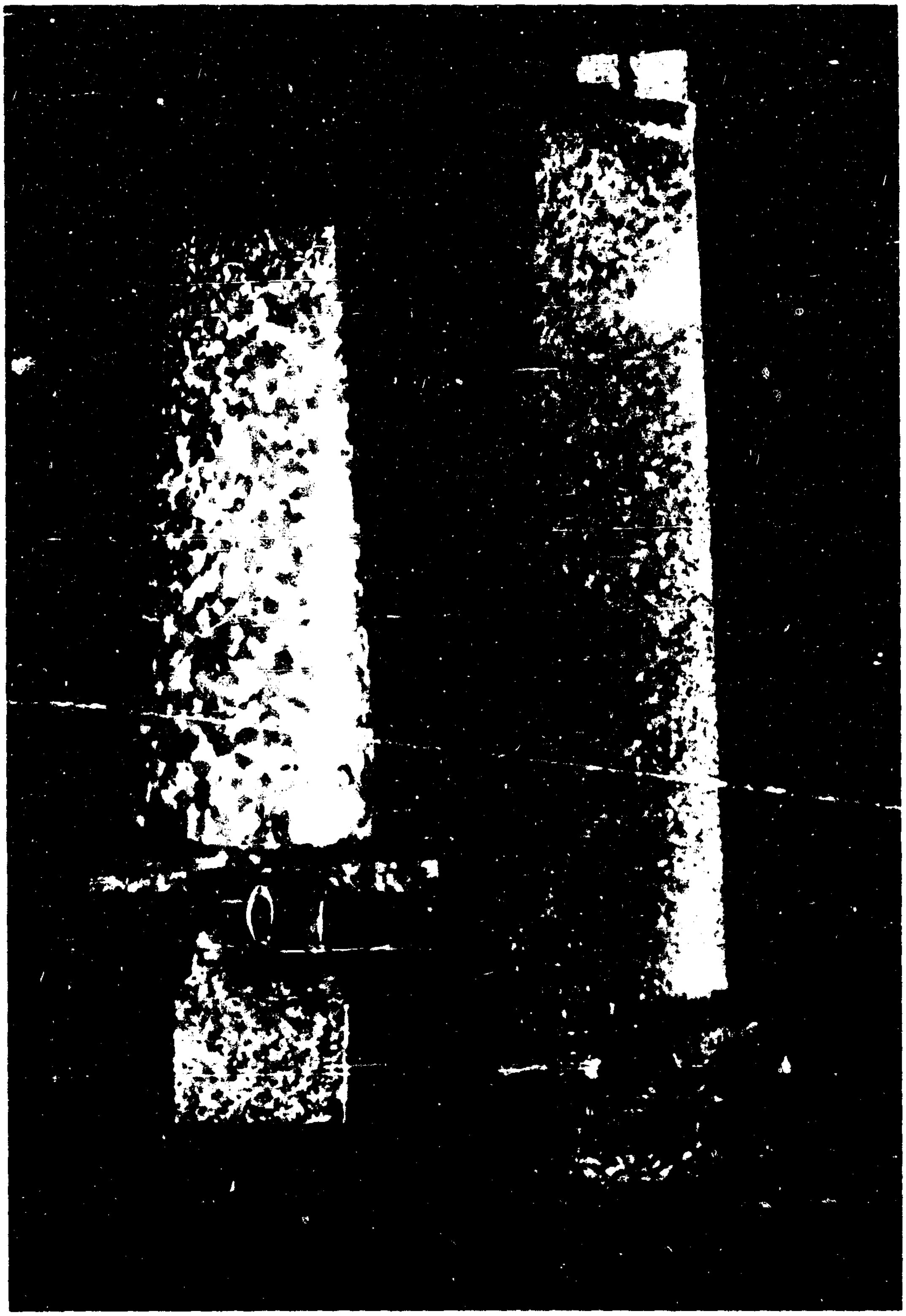

Figure 40. J58 Turbine Blades Cast to the Grain X Process Showing Uniform Structure and Equiaxed Grains. PWA-658 (IN-100)

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To enforce the controlled processes thus arrived at, a number of personnel were hired by the casting vendor and placed on the operating line solely to monitor and enforce the control requirements. Finally, the entire casting processes and limits of variation of the critical operations were incorporated into a "Frozen Process" for J58 first and second stage turbine blades which cannot be altered by the casting vendor without prior approval of P&WA.

As a consequence of the "Frozen Process" and the development of highly beneficial heat treatment, blade castings have been produced which, as far as is known, have never been equalled in quality and performance, especially when the complexity of the alloy composition, the blade configurations, and the operating environment are simultaneously considered. The latter involves the most severe temperature and stress conditions ever encountered in a production turbine engine.

The operating reliability record of J58 1st and 2nd stage Grain X turbine blades of IN 100 is outstanding. In over 20,000 hours of testing, the J58 engine has never experienced an IN 100 turbine blade failure in either experimental or field engine experience under normal operating conditions. Individual IN 100 blades in the J58 engine have been operated in excess of 1200 hours and have shown negligible sigma phase formation when examined from the blade tip to the root platform. This operational record is supported by a statistical analysis of 1800°F stress rupture qualification test results from specimens machined from 300 blades representing 92 production heats of blade castings for engine operation. This analysis shows a remarkably high degree of reproducibility of stress rupture properties.

A similar analysis of <u>current forged U-700</u> blade stress rupture properties for other engines shows <u>less</u> reproducibility than do the <u>cast IN 100 J58</u> blades. (See figure 41.) This type of mechanical property reproducibility for complex blade casting configurations of this size, as opposed to less complex smaller blade forging configurations, is unique.

In view of the most favorable operating record of IN 100 blade castings in the J58 engine and the inherent mechanical property capabilities of the alloy in terms of JTF17 engine requirements, IN 100 is specified

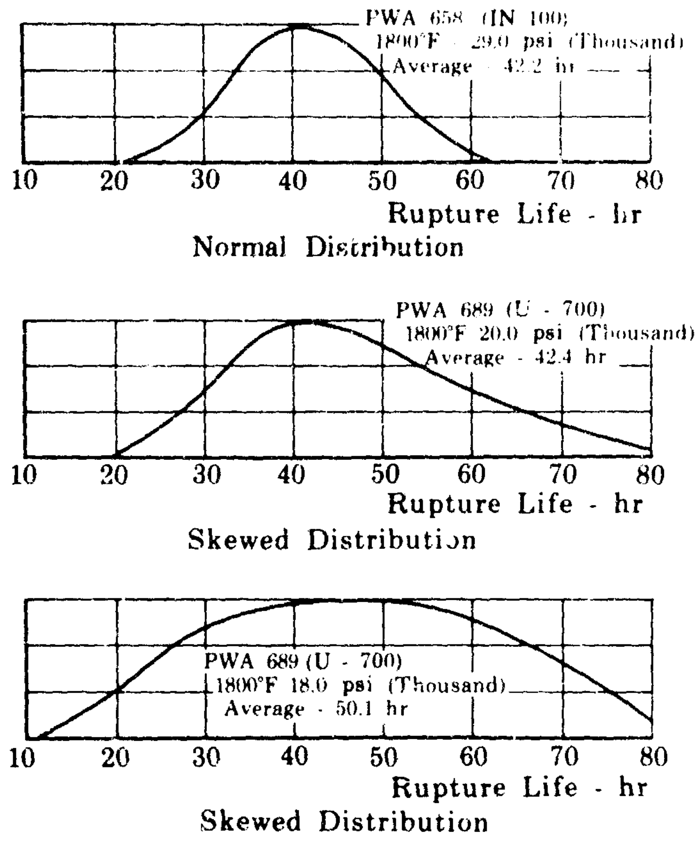

Figure 41. Variability in Stress Rupture Life of Cast and Wrought Turbine Blades — FD 16600 FII

for first, second, and third stage turbine blades for the JTF17 engine.

(2) Vanes

First Stage Vane	PWA 1035 (TD Nickel)
First Stage Vane (Alternate)	PWA 664
Second Stage Vane	PWA 658 (IN 100)
Third Stage Vane	PWA 658 (IN 100)

In view of the success experienced with PWA 664 vanes (See proposed alloys following page), the material has been specified as a back-up for PWA-1035 (TD Nickel) for first stage turbine vane application. As has been explained previously, TD Nickel enjoys a decided strength advantage over all conventional nickel and cobalt base superalloys at temperatures in excess of 2000°F, as well as a much higher melting point. Considering the turbine inlet temperatures at which the JTF17 will eventually operate, TD Nickel has been specified.

Extensive production engine operation experience with PWA-658 (IN 100) second stage vanes has been logged in the J58 engine. These vanes have, like PWA-658 (IN 100) blades, operated without failure in the J58 as a result of the composition, process controls, and heat treatment which have been used for blades. Because of this operating experience, the adequacy of the mechanical properties of these vanes, and the low density of IN 100, it has been specified for the second and third stage vanes for the JTF17 engine.

Coatings specified for protection of IN 100 turbine blades and vanes and PWA-664 turbine vanes are discussed subsequently in the section entitled "Coating Specified and Description of Coating Processes", Section III, Page 11 of this report.

2. Proposed Alloys

a. PWA 664* (Covered by U.S. Patent No. 3,260,505.)

As a follow-on to the development of the IN 100 turbine blade with Grain X structure in late 1963, a second and most significant step was taken in extending the concept of controlled grain structure in turbine blade and vane hardware. The Advanced Materials Research and Development Laboratory of P&WA (AMRDL) developed a casting technique involving directional solidification which could be applied to precision blade castings. After an extended development program performed within AMRDL to establish important parameters and develop adequate casting equipment for making hardware, the process was turned over to a blade casting supplier for the production of blade and vane hardware for engine operation.

In april of 1965, United Aircraft Corporation disclosed to the public this concept of directional solidification as applied to gas turbine blades and vanes. Since this introduction, extensive laboratory and engine testing has shown directional solidification coupled with appropriate heat treatment to be one of the most significant metallurgical developments in the aircraft industry since the introduction of investment casting techniques.

Up to the time of introduction of directional solidification by United Aircraft Corporation, many of the strongest cast turbine blade materials were limited by their low ductility, poor thermal shock and ballistic impact resistance, and their lack of third stage creep. In particular, Mar-M200, as conventionally cast, was limited in overall usefulness in high performance engines due to low intermediate temperature ductility as previously discussed. Due to this low ductility, the alloy was unable to plastically deform locally in areas of high stress concentration in blade roots to lower stress concentrations sufficiently to avoid premature cracking.

By applying directional solidification techniques to Mar-M200, the material's grain orientation has been altered to promote increases in both intermediate temperature ductility and strength. In addition, thermal shock, ballistic impact, and bow and creep resistance have been significantly improved. Today PWA 664, directionally solidified Mar-M200, is the strongest cast turbine blade material in existence. A comparison of tensile and stress rupture properties as well as ballistic impact characteristics to conventionally cast Mar-M200 is presented in Figures 42 through 45.

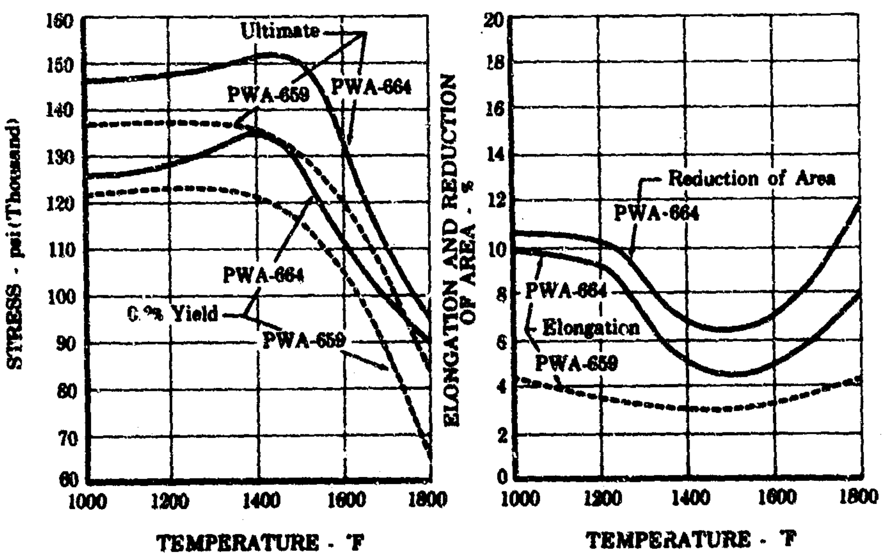

Figure 42. Tensile Properties of PWA-664 and PWA-659

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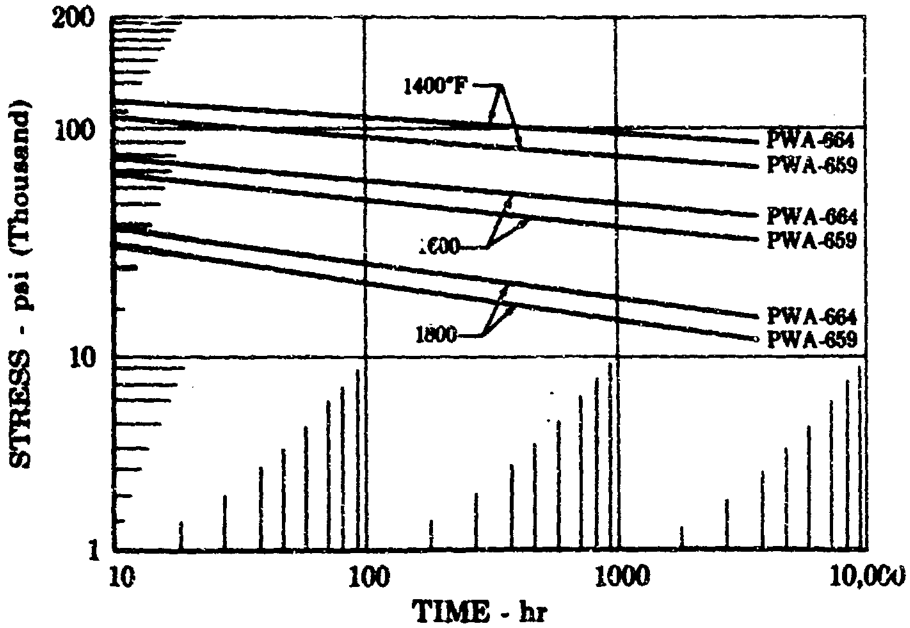


Figure 43. Stress Rupture Strength of PWA-664 and PWA-659 FD 16602 FII

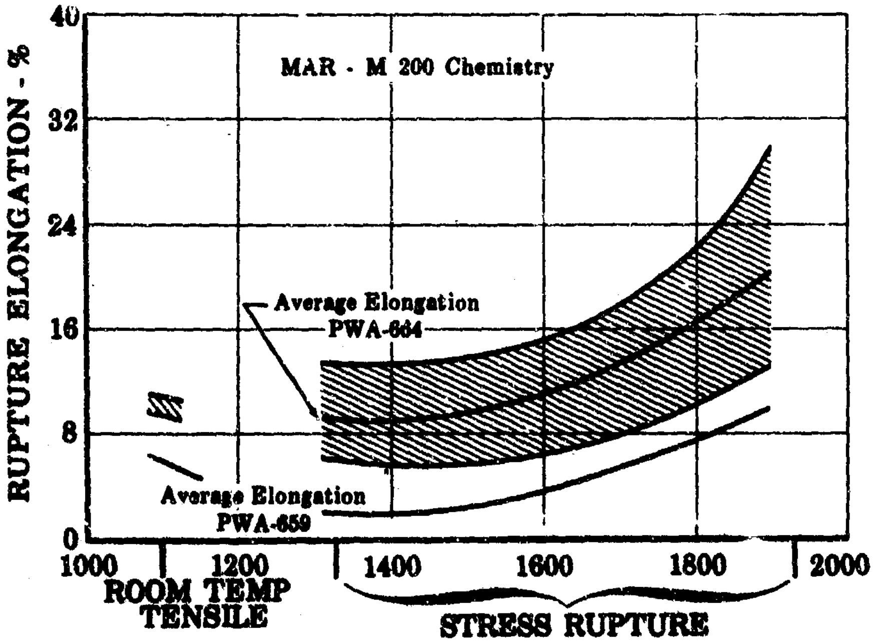
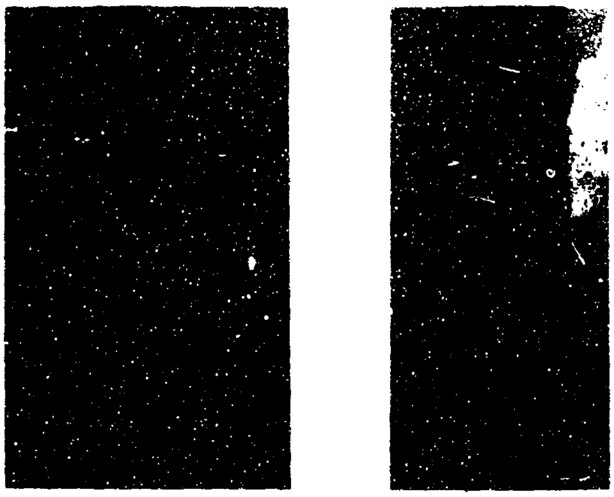


Figure 44. Rupture Elongation of PWA-664 and PWA-659 FD 16603 FII



PWA-659 JT4 Turbine Blade
Note Brittle Fracture and
Cracking Caused by Impact

PWA-664 JT 4 Turbine Blade
Note Absence of Brittle
Failure or Cracking

Tests Conducted Using a .65-gm Pellet at a Velocity of 1000 ft/sec

Figure 45. Comparison of Ballistic Impact Resistance to PWA-664 and PWA-659 (Mar-M200) FD 16604 FII

From these curves, the mechanical property advantages that PWA-664 exhibits over conventionally cast material is obvious. Inherently, PWA-664 derives its intermediate temperature ductility, excellent strength, thermal shock, ballistic impact, and bow resistance from an assembly of columnar grains with an (001) orientation which differs markedly from conventionally cast materials with a random grain orientation. A photograph showing the columnar PWA-664 orientation in J58 1st and 2nd blades is shown in figure 46.

During creep conditions at intermediate temperatures, most of the conventionally cast nickel base alloys such as Mar-M200 are subject to intergranular cracking and rapid crack propagation, lack of third stage creep, and subsequent premature failure. The absence of transverse grain boundaries normal to the stress in PWA-664 eliminates the occurrence of intergranular cracking; and, therefore, increases useful impact, thermal shock, and creep capability.

Laboratory investigation of PWA-664 has been supplemented by extensive engine test programs involving turbine blade and vane applications in the JT4 and J58 engines resulting in the incorporation of this alloy in production J58 engines. A wide variety of tests have been run on the

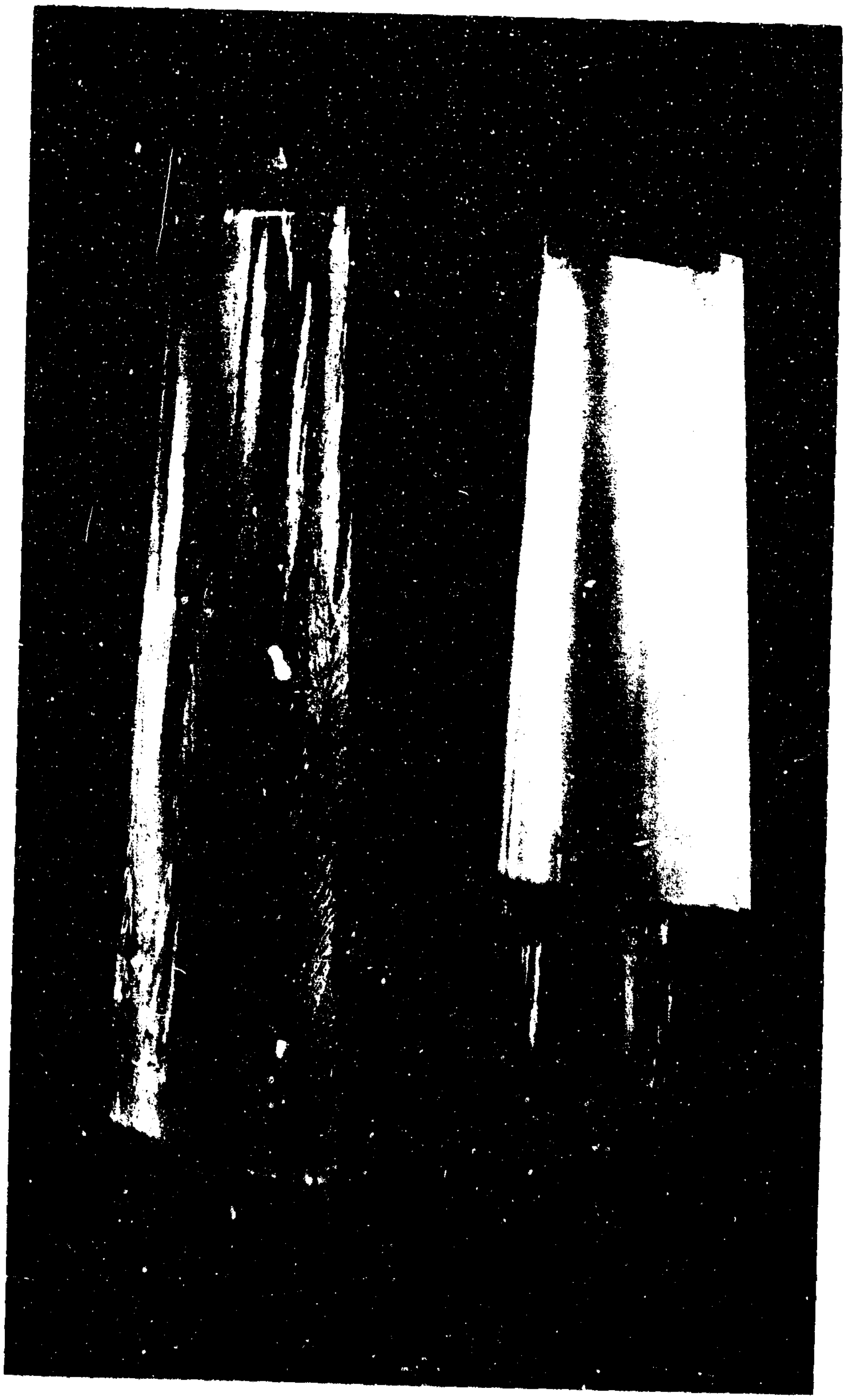


Figure 46. J58 Turbine Blades Showing the Controlled Directionally Solidified Structure PWA-664

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alloy and comparisons made to other competitive alloys. The PWA-664 blades have displayed a significant measure of superiority over these other alloys, including IN 100, in strength performance.

Engine operation and laboratory testing of PWA-664 turbine blades and vanes is continuing on an intensive basis in order that the advantages inherent in this material can be utilized for upgrading the performance of the JTF17 engine when appropriate.

b. PWA 1409 (MONOCRYSTALOY, UAC Trademark): Covered by U.S. and Foreign Patents Pending

Realizing that continuing research and development in materials technology is essential in order to extend life and improve high temperature strength, P&WA has succeeded in expanding upon the principle of directional solidification.

Recently a new concept has been translated into casting technology which in its application is as revolutionary and promising as PWA-664 and offers potential for increase in turbine blade and vane capability beyond current levels of performance.

In February of 1966, MONOCRYSTALOYS* were introduced to the public. MONOCRYSTALOYS* are precision cast, single crystal alloy components for gas turbine engines. As grain boundaries are completely absent in a single crystal components, thermal shock and ballistic impact capabilities as well as strength have been upgraded.

A photograph of a single crystal 2nd-stage J58 blade, along with other 2nd-stage blade castings showing the evolution of P&WA's controlled structure casting development program, is shown in figure 47. To date, very favorable results have been obtained in material of Mar-M200 designated as PWA-1409. Optimum crystallographic orientation for best combination of properties for turbine blade application has been found to be with the (001) direction aligned parallel to the major axis of stress. Reproducibility of structures with this process has been excellent and the required casting procedures lend themselves to hardware production.

*UAC Trademark

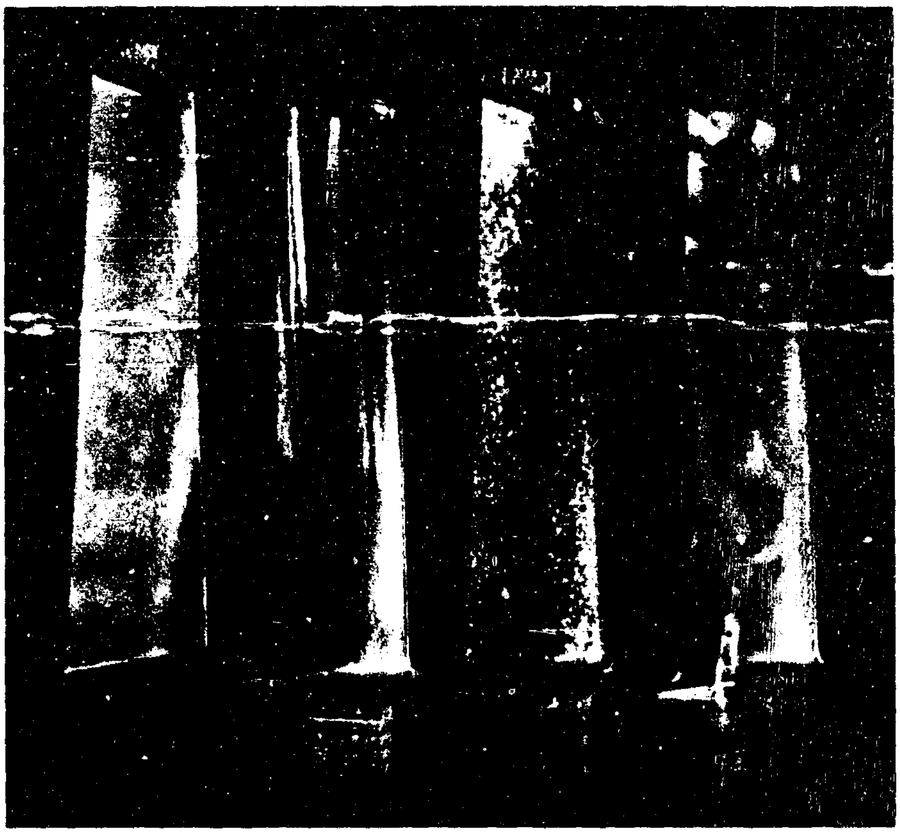
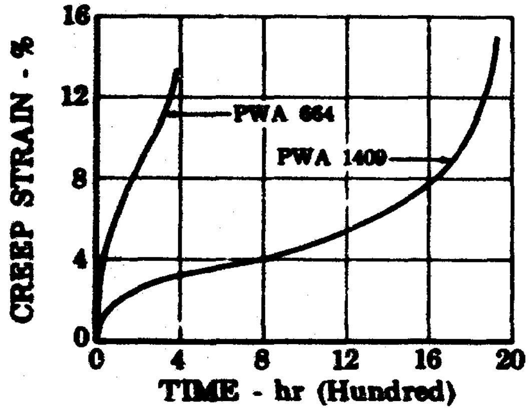


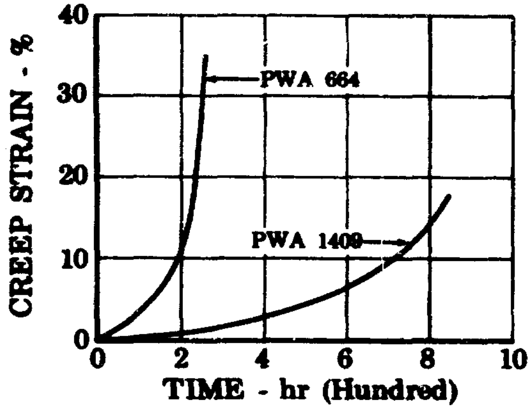
Figure 47. Evolution of Controlled Structure Casting Development J58 Turbine Blade Castings Exhibiting, From Left to Right Uncontrolled, Grain X, Directionally Solidified (PWA-664), and Single Crystal (PWA-1409) FE 59719 FII

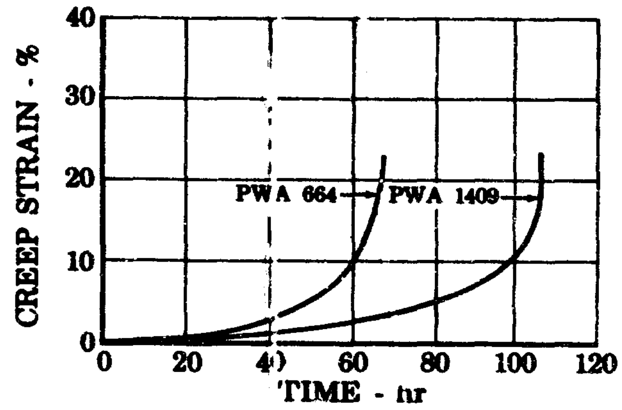
Chief advantages of PWA-1409 (MONOCRYSTALOY* Mar-M200) material over the PWA-664 (Directionally cast Mar-M200) and PWA-659 (Conventional Mar-M200) alloys appear to lie with its exceptional thermal shock behavior, ballistic impact, and outstanding creep resistance and rupture life. Curves comparing typical heat treated PWA-1409 creep resistance and rupture strength to PWA-664 material are presented in Figure 48.

PWA-1409 is a strong candidate for turbine blades and vanes for furthering the development of the JTF17 for growth potential. It represents an extremely important technological advancement and one from which all future high performance gas turbine engines stand to benefit. Currently, turbine blades have been produced and are undergoing rigorous engine tests to further define and establish the material's interesting potential.

*UAC Trademark







Matl	1400°F - 100 psi		
	Rupt Life	% Elong	Min Creep Rate
PWA-664	386.0	17.6	5×10^{-5}
PWA-1409	1914.0	14.5	2×10^{-5}

Matl	1600°F - 50 psi		
	Rupt Life	% Elong	Min Creep Rate
PWA-664	280.0	35.8	7.7×10^{-5}
PWA-1409	848.0	18.1	1.4×10^{-5}

Matl	1800°F - 30 psi		
	Rupt Life	% Elong	Min Creep Rate
PWA-664	67.0	23.6	25.6×10^{-5}
PWA-1409	107.0	23.6	16.1×10^{-5}

Figure 48. Creep Behavior of PWA-664 and PWA-1409

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c. Application of Directional Solidification and Single Crystal Processes

It is appropriate to point out that with the introduction of directional solidification and single crystal technology capable of producing blade and vane hardware, and the attendant upgrading of mechanical properties afforded by the preferred orientations and unique grain boundaries involved, P&WA is now in the process of evolving alloy compositions with properties inherently superior to Mar-M200 to which these casting processes may be applied for the development of hardware superior to PWA-664 and PWA-1409. As has been indicated, primary emphasis is upon the imparting of oxidation-erosion and sulfidation resistance to a sufficiently strong alloy to negate the need for the protective coating.

d. PDRL 163 (Modified)

Pursuing this goal of uncoated blade and vane operation within the supersonic engine environment, P&WA initiated a series of investigations to develop a high strength composition for turbine blade and vane application that would resist the effects of oxidation-erosion and sulfidation for sustained periods of time. Working jointly with independent research facilities, these studies were directed toward producing an alloy composition exhibiting strength comparable to IN 100 with oxidation-erosion and sulfidation resistance approaching that of present coated alloys.

Preliminary exploration work was conducted on the nature of the turbine environment and its influence on the degradation of superalloys; this led to the conclusion that initial development should be directed toward strengthening by alloy modification to give precipitation hardening to nickel alloy systems already possessing good oxidation-erosion and sulfidation resistance. This course was considered most prudent since the nature and mechanics of strengthening mechanisms were much better understood than the reactions and interaction occurring in a sulfidizing operating environment.

After analyzing data and characteristics of basic alloy systems, P&WA entered a program which had been initiated by a material supplier to fully develop the capabilities of the alloy PDRL 163. This alloy, based upon environmental tests, was found to possess exceptional oxidation and sulfidation resistance to simulated engine atmospheres. The basic limitations of PDRL 163 had been strength below desired levels and an inability to achieve mechanical property results at intermediate temperatures on a repetitive basis within acceptable confidence limits. Working to eliminate these deficiencies, the material supplier began compositional changes to determine if both strength and reproducibility could be simultaneously increased. Through analyses of both matrix and secondary phase additions, it was found that additions of cobalt effectively increased intermediate temperature ductility with the added features of both improvement in strength and reproducibility. At additions of approximately 10% cobalt, the strength, though still below that of the program objectives, approaches suitable levels. Results of creep-rupture testing are shown in figure 49.

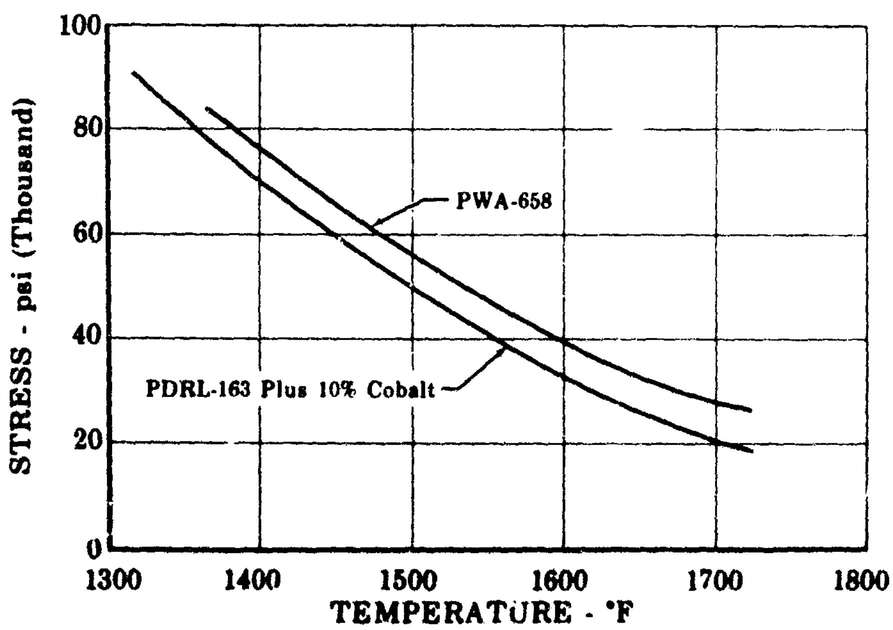

Figure 49. Creep Rupture Strength of PWA-658 and PDRL-163, 500 Hours — FD 16606 FII

With environmental tests confirming no loss in oxidation-erosion and sulfidation resistance, work has been redirected to a PDRL 163 plus 10% cobalt base. Additional heats of material are being prepared to investigate the effect on strength of further heavy element additions with a simultaneous change of the basic aluminum-titanium hardening content. Recognizing again the importance of correct thermal treatment, concurrent studies are in progress to define proper ageing sequences to ensure maximum alloy property response under engine operating conditions.

Following satisfactory completion of these program phases, final investigations will be directed toward producing optimum engine hardware utilizing directional solidification processes.

e. TRW 2278

Recently, a material supplier completed a series of heavy element modifications to a high aluminum, nickel base material in an effort to increase strength while maintaining a high degree of oxidation-erosion and sulfidation resistance. The final product was an alloy designated TRW-2278 which, from initial testing, approaches the basic objectives of a turbine blade and vane alloy that can operate satisfactorily in the JTF17 without a protective coating.

Testing by P&WA has shown excellent oxidation and sulfidation resistance of the alloy to simulated engine environment. Tensile and creep-rupture results approach those of IN 100. Creep rupture data are shown in figure 50.

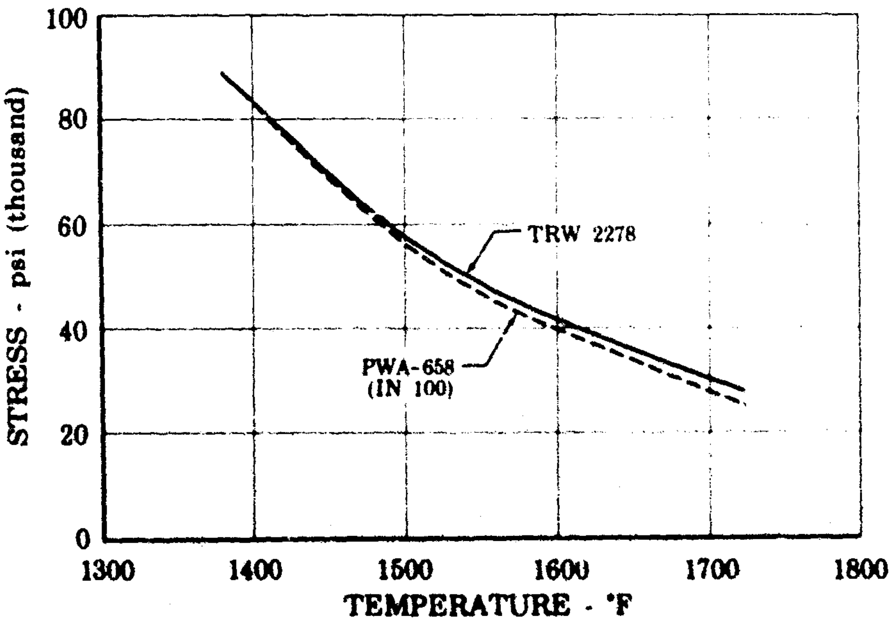

Figure 50. Creep Rupture Strength of PWA-658 and TRW 2278, 500 Hours FD 16607 FII

With the degree of success thus far experienced, P&WA had now placed an order for directionally solidified blade and vane hardware of this material for complete laboratory evaluation. The evaluation to be conducted on these parts will provide a full assessment of property acceptability of this alloy composition.

f. Fundamental Mechanics of Sulfidation

P&WA is presently engaged in a research program aimed at establishing the basic mechanism responsible for the accelerated metal deterioration associated with sulfidation of nickel base superalloys. More than one-hundred and fourteen experimental heats representing various compositional ranges in the nickel base superalloy class have been cast and subjected to simulated engine sulfidizing conditions in an effort to study the effect of the individual alloy constituents. In several instances the corrosion rates of experimental alloys have been calculated prior to casting and then substantiated in rig testing. Of particular importance is the fact that the studies have been performed on compositions representative of existing superalloys and not on binary or ternary compositions which have, in many instances, shown no correlation with fully alloyed compositions.

Working closely with a material supplier, several alloys tailored for sulfidation resistance have been thoroughly evaluated and cast into engine test hardware. Testing will be performed to establish documented evidence of the superiority of these compositions.

Alloy development work continues on an expanding and accelerated scale with the objective of developing a completely sulfidation resistant nickel base superalloy with inherent strength comparable or superior to any alloy in existence today.

g. IN 100 (Modified)

The International Nickel Company began an investigation of the basic IN 100 composition in response to the sigma phase problem encountered by an early user of the alloy who specified a titanium level above that recommended by the alloy developer. A study of the influence of cobalt on sigma formation was a part of this investigation. The very small amount of sigma found by P&WA in long time operated blades has been identified as $(Cr_2Mo)(Co_{1.7}Ni_{0.3})$. This finding led to a reduction of cobalt from the nominal 15% specified in PWA 658 to 10% in order to reduce the probability of sigma formation. Calculation of the electron vacancy numbers with this modified composition shows a change from N_v=2.21 to 2.06 where N_v=2.32 or above suggests a sigma prone composition.

An investigation was conducted using heats cast with varying cobalt levels while maintaining all other elements within PWA-658 specifications. Results of testing and subsequent structural evaluation by International Nickel Company and P&WA showed that not only had the propensity for sigma formation been reduced by reducing the amount of cobalt but, at the 10% level, a notable improvement in both intermediate temperature strength and ductility had been achieved. Tests were conducted from 800 to 2750 hours at sigma forming temperatures, and the subsequent microstructural evaluation showed no evidence of sigma formation.

With additional tests supporting the strength improvement at intermediate temperatures, two clusters of 2nd-stage J58 turbine blades were cast for hardware evaluation. Results obtained from creep-rupture testing of specimens machined from blades are shown in figure 51. PWA-658 (IN 100) creep results of nominal composition is included for comparison. Both coated and uncoated specimens were used in the test program and compatibility of existing P&WA coatings was rated as excellent. Root and airfoil samples are still running in a continued long time evaluation of alloy stability. Tests supplementing the above program have also shown that the P&WA heat treatment developed for the base PWA-658 (IN 100) composition still achieves the best balance of intermediate and high temperature properties when compared to other heat treatments evaluated. Further studies are in progress to test the effect created by introducing a solutioning-homogenization treatment prior to final ageing. Initial tests incorporating this type of approach have shown improvement in high temperature rupture life but, as yet, intermediate temperature tests have not been concluded.

Future plans call for additional testing within an engine environment, pending satisfactory completion of the present evaluation, and for further evaluation of directionally solidified configurations. Based on final J58 engine test acceptability, consideration will be given to the modification of the present PWA-658 specification.

h. Cast Nickel-Molybdenum-Aluminum Base Alloys

In 1965, work was initiated at FRDC on a conventionally cast ternary alloy system which has shown exceptional potential for advanced cast turbine vanes. Tensile, stress rupture, and oxidation properties have

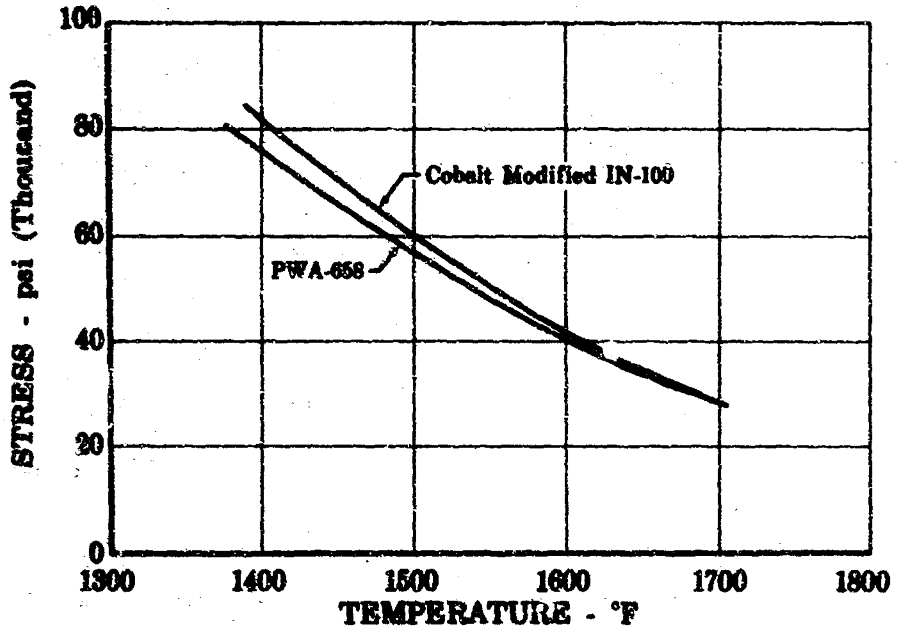

Figure 51. Creep Rupture Strength of PWA-658 and Cobalt Modified IN-100, 500 Hours FD 16608 FII

been generated for the material, which exhibit a significant superiority over those of cast cobalt base alloys. The alloy has shown usable stress rupture capability in the 2000°F to 2300°F range, high melting temperature (in excess of 2350°F), excellent castability, good coatability, and low density (0.297 lb/in.^{3}). Simplicity of the alloy is such that raw material costs should be low in comparison to other more complex turbine vane and blade alloys.

Preliminary Ni-Mo-Al tensile and stress rupture data generated from conventional, investment cast test bars are compared to a currently used cobalt base alloy and TD Nickel (PWA-1014) and presented in figures 52 and 53, respectively. Ni-Mo-Al stress rupture strength is superior to Mar-M302 over the total temperature range evaluated. Ni-Mo-Al is stronger in stress rupture than TD Nickel up to 1900°F.

Tensile strength of Ni-Mo-Al in the 1800°F to 2200°F range shows it to be one of the strongest high temperature alloys ever developed for vane application. Due to its excellent castability, it is conceivable that single crystal or directional solidification techniques, when utilized on this material, will result in even greater temperatures and strength capability than that currently demonstrated.

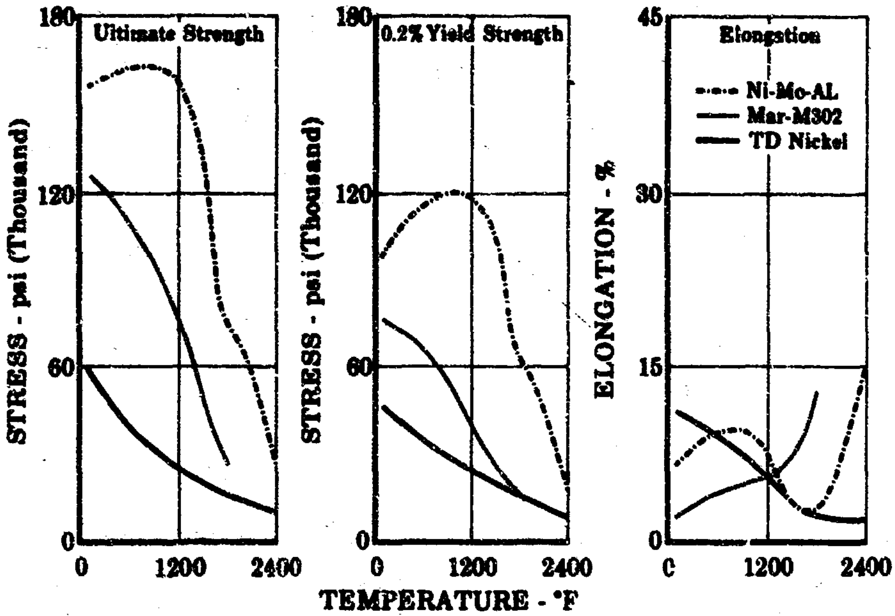

Figure 52. Tensile Properties of Mar-M302, TD Nickel, and Ni-18 Mo-8AL

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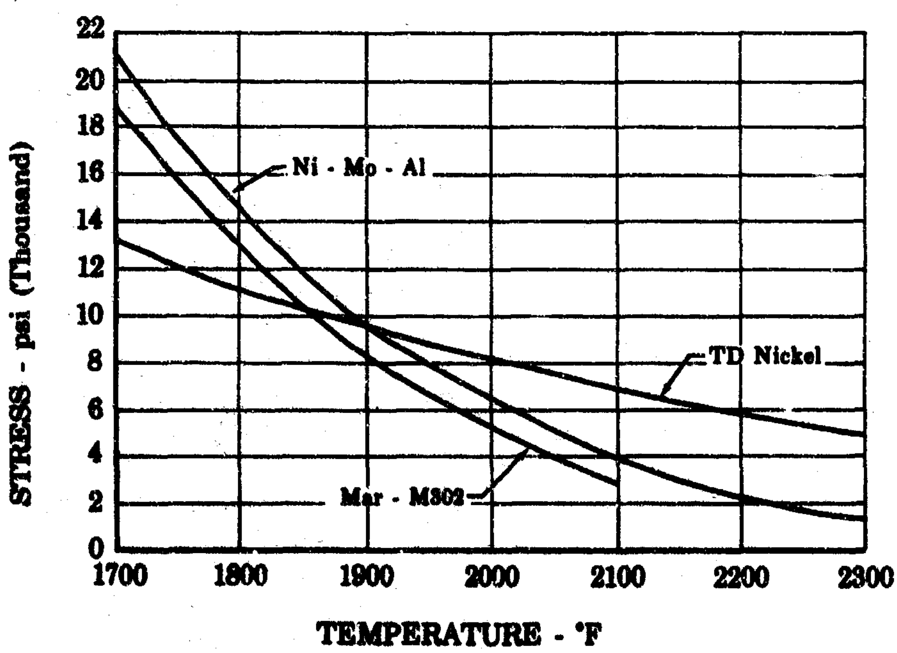

Figure 53. Stress Rupture Strength of Mar-M302, TD Nickel, and Ni-18Mo = 8Al, 100 Hours

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The strengthening mechanisms of the compositions studied are as follows:

1. Solid solution strengthening by molybdenum in the nickel matrix
2. Precipitation stregthening with a very stable Ni_3Al phase
3. Ordering reactions resulting from the heat treatment.

Tensile strengths in the 1000°F to 1400°F range, which are superior to those at room temperature, strongly indicate that an ordering reaction may be occurring in the material during exposure to elevated temperature.

Stoichiometrically, the composition is such as to favor the formation of Ni_3Al, which is a known ordered intermetallic compound. X-ray diffraction studies conducted on Ni-Mo-Al material, both as-cast and heat treated, showed that the heat treated material exhibited a greater degree of ordering than did the as-cast material.

It is not felt by P&WA that the optimum composition for Ni-Mo-Al has been realized, and chemistry modification programs are in progress for further development of the composition. The aims of these modifications will be to effect increases in intermediate temperature strength and high temperature oxidation resistance.

Based on the outstanding test bar results obtained to date on one of the compositions, experimental quantities of JT4 first stage turbine vanes have been investment cast with encouraging results. Thermal shock and bow tests are currently being conducted in an attempt to evaluate these characteristics.

Although much of the data generated to date for alloys in the Ni-Mo-Al system is preliminary, it is sufficiently encouraging to warrant additional work. Extension and intensification of P&WA efforts in this area could well result in a low cost investment cast turbine blade and vane material for the JTF17 engine.

G. CAST COBALT BASE ALLOYS

1. Specified Alloy - None

2. Proposed Alloys - Turbine Vanes

a. MA 51 System

P&WA is performing alloy development work on cast cobalt base superalloys for turbine vane use. As has been discussed, the oxidation-erosion and sulfidation resistance of existing commercially available nickel base alloys suitable for turbine blade and vane applications is inadequate for operation in the JTF17 engine without a protective coating. P&WA's extensive efforts toward development of a nickel base superalloy with improved erosion and sulfidation resistance to lessen or obiate the dependence on a coating have been described in detail in the preceding section. Traditionally, cobalt base alloys have been considered to exhibit inherently greater sulfidation and thermal shock resistance and higher incipient melting temperature than nickel base alloys; these features are particularly important for first stage turbine vane applications. Turbine inlet temperatures encountered in high Mach number engines, as well as in high performance subsonic commercial turbine engines, have increased to the extent that the margin of sulfidation and oxidation-erosion superiority of the cobalt base alloys over the nickel base superalloys has been diminished significantly; the difference is now essentially indiscernable.

In 1964, the FRDC materials laboratory initiated work on a cobalt base alloy system in an attempt to establish a composition with a higher melting temperature that could be run successfully in the J58 engine without a coating. The advantage of such an alloy from the standpoint of reliability and cost are obviour.

It has long been known that cobalt base alloys derive the bulk of their strength from solid solution and carbide dispersion strengthening. Traditionally, chromium, tungsten, and molybdenum have found usage as solid solution strengtheners; and tantalum, columbium, titanium, and zirconium have been used as carbide formers and strengtheners. From an oxidation viewpoint, chromium, aluminum, tantalum, and recently yttrium, have been found beneficial. Nickel has been found advantageous in promoting thermal fatigue resistance.

Based on this knowledge, X-40 (AMS 5382) was selected for modification, utilizing tantalum and yttrium as the modifying elements. By combining the oxidation characteristics of chromium, tantalum, and yttrium with the solid solution strengthening benefits of tungsten in a cobalt-nickel-carbon matrix, P&WA has succeeded in developing a cobalt base alloy which exhibits outstanding sulfidation resistance as well as an overall balance of properties which make it extremely attractive for uncoated gas turbine vane applications. Composition of the alloy, known as MA 51, and designated PWA-648 is shown and compared to several other vane alloys in table 8.

Table 8. Compositions of Typical Gas Turbine Vane Materials

Specification	Alloy	C	Cr	Ni	W	Ta	Other	Co
PWA 648	MA 51	0.46	25.5	10.5	7.5	5	.6Y	Bal
AMS 5382	X-40	0.50	25.5	10.5	7.5	-	---	Bal
PWA 653	WI 52	0.45	21	---	11	-	2 Cb	Bal
PWA 657	Mar-M302	0.86	21.5	---	10	9	0.2 Zr	Bal

Laboratory investigation of PWA-648 (MA 51) has shown it to have the highest thermal fatigue strength and oxidation-erosion and sulfidation resistance of all commercially available cobalt based turbine vane materials. Melting point of the alloy is also higher than any of the older turbine materials, being approximately 100°F higher than PWA-657 (Mar-M302), for example. A comparison of the oxidation, sulfidation, stress rupture strength, and incipient melting characteristics of PWA-648 (MA 51) with other vane materials given in table 9.

Table 9. Oxidation, Sulfidation*, Stress Rupture and Temperature Characteristics of MA 51 (PWA-648) as Compared to Other Cast Vane Materials

Alloy	Oxidation Rating	Sulfidation Rating	Stress Required to Induce Rupture in 200 Hours at: 2000°F	1800°F	Incipient Melting Point
PWA 648 (MA 51)	B	A	5800 psi	9,000 psi	2385°F
PWA 1014 (TD Nickel)	C	A	6200 psi	8,800 psi	2650°F
PWA 653 (WI 52)	F	B	4000 psi	8,400 psi	2370°F
PWA 657 (Mar-M302)	D	C	5700 psi	9,800 psi	2260°F
PWA 664	E	D	7000 psi	20,000 psi	2225°F
PWA 663 (B-1900)	A	E	7500 psi	22,000 psi	2240°F

*Alloys are in decreasing order of oxidation and sulfidation resistance.

Engine test results of PWA-648 (MA 51) first stage turbine vanes run uncoated for 250 hours in the J58 engine established that vane bowing was significantly less than that exhibited by equivalent coated PWA-657 (Mar-M302) vanes. The test was conducted for 150 hours with turbine inlet temperature in excess of 2000°F. Bowing of these vanes was considered as comparable to widely used coated PWA-653 (WI52). Visual and metallographic examination of the vanes after removal from the engine revealed negligible oxidation and no microstructural evidence of sulfidation. The appearance of two typical uncoated PWA-648 (MA 51) first stage vanes after 250 hours of J58 engine operation is shown in figure 54.

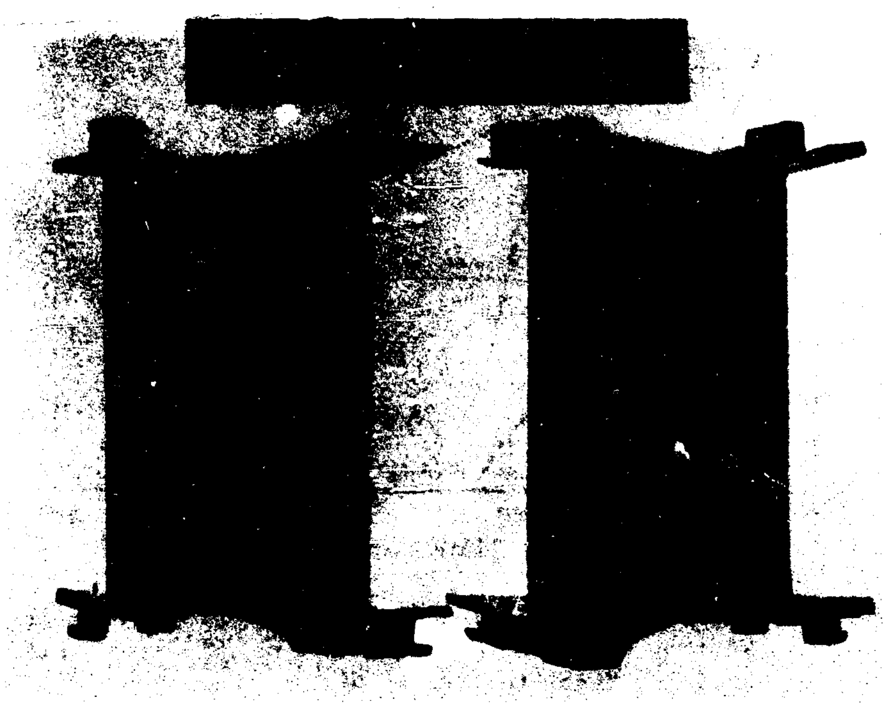

Figure 54. Condition of Uncoated MA-51 1st-Stage J58 Turbine Vanes After 250 Hours of Engine Operation. FE 59807 FII

Laboratory and engine evaluation of PWA-648 (MA 51) is continuing. As a result of the outstanding oxidation and sulfidation resistance of the alloy, sets of vanes have been produced and will be tested in the JT4 and JT8D engines in the uncoated condition to evaluate the performance relative to coated PWA-653 (WI52) and PWA-657 (Mar-M302) vanes. If the alloy performs as expected, increased reliability and cost saving will be realized for these engines.

Additional modification work on the MA 51 alloy involving aluminum additions has resulted in the most oxidation-erosion and sulfidation resistant alloy ever evaluated on P&WA laboratory rigs. A comparison of accelerated oxidation-erosion results of modified MA 51 to conventional MA 51, as well as to other conventional alloys, is presented in figure 55. Aluminum modifications to the MA 51 system, however, are detrimental to the high temperature strength of the material; and, therefore, further work is underway in an attempt to regain the lost strength without impairing the improved oxidation resistance.

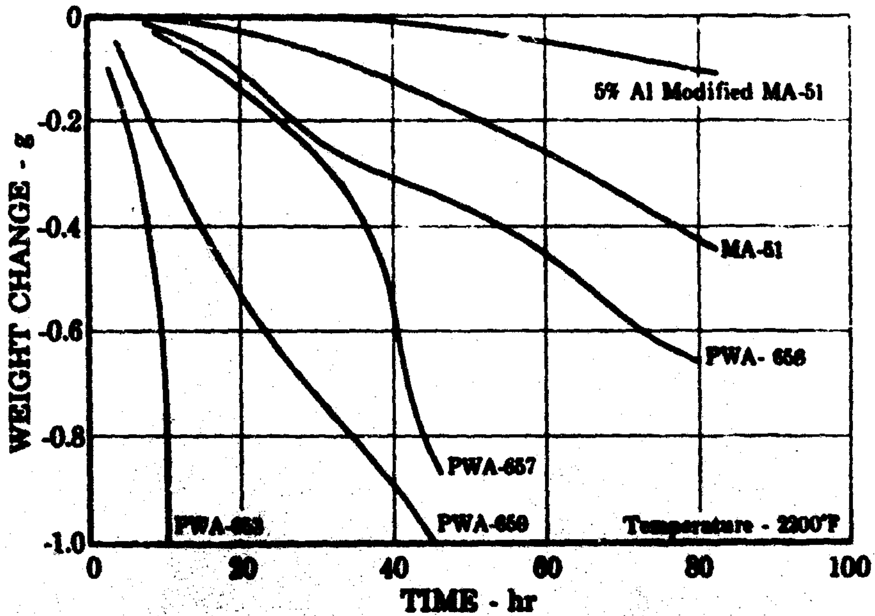

Figure 55. Accelerated Oxidation-Erosion Testing Comparing Aluminum Modified MA-51 to Typical Ni and Co Base Vane Alloys

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Basic studies are underway in an attempt to understand the mechanisms responsible for the effect of aluminum on oxidation resistance and mechanical strength. These investigations, coupled with the development of directional solidification techniques, could well result in a composition with a level of performance above that currently available with any known vane composition.

H. METALLURGICAL CONTROL OF MAJOR ROTATING PARTS

In the previous subsections, the necessity for close control of material processes during manufacture has been established several times (for example, the need to limit the presence of segregates in titanium disks). Because of the prime importance of maintaining the integrity of major rotating parts and the close metallurgical surveillance required for such maintenance, it is appropriate to discuss metallurgical control of major rotating parts in this report.

Volume IV, Report F, Section III contains a comprehensive discussion of P&WA quality control systems, without reference to specific categories of parts. It should be understood that the quality controls discussed in this subsection are not restricted to major rotating parts but are applicable in some measure to other parts as well.

Types of Parts included in this category are hubs, disks, shafts, and blades.

The Pratt & Whitney Aircraft Source Approval System limits the sources of critical parts to qualified vendors who possess particular skills or who have acquired specialized knowledge and ability through cooperation with P&WA during development of like parts and materials. The P&WA Purchasing Department will use only Engineering Department-designated sources, when source approval is required, or will negotiate suitable programs to approve additional sources if appropriate.

The following note appears on the P&WA drawing for each part requiring Source Approval:

> "Parts supplied to this drawing shall be in strict accordance with samples approved by Pratt & Whitney Aircraft Engineering Department unless prior written approval is given to subsequent change."

An Engineering Source Approval Data List is issued for each part requiring Source Approval. This Data List designates the approved source(s) for each of the operations which are considered critical in the manufacture of the part. A typical data list specified approved sources for:

- Ingot
- Forging or Casting
- Completed Part (Machining)
- Special Operations, such as broaching, hard-facing, etc.

Initial Qualification consists of the Vendor demonstrating his ability to produce parts that conform to all quality requirements and operate satisfactorily in experimental engines.

Conformance to quality requirements includes the following non-destructive testing:

Forgings (Disks)	Castings (Blades)
Chemical Analysis - each heat	Chemical Analysis - each heat
Sonic tests - each billet or ingot	Radiographic Inspection - each part
Macro-etch - each ingot	Anodic Etch - each part
Macro-etch - each multiple	Grain Size (or orientation) Etch - each part
Hardness testing - each part	Fluorescent Penetrant Inspection - each part
Sonic testing - each part	
Grain Size testing - each part	
Mechanical Property testing - each part (integral test material)	

Destructive testing of one or more parts from the initial run is performed by the Vendor and confirmed by P&WA tests. A forging from each new die configuration is cross-sectioned and etched, and a photograph furnished to P&WA for approval of grainflow pattern. Also, mechanical property specimens are machined from the part and tested for conformance to material specification requirements. Location and type of mechanical property requirements are defined by P&WA Materials Laboratories, working in conjunction with Design and Project Engineering. Following are typical requirements:

Property	Flat (Forged) Disks	Cast Turbine Blades
Room temp. tensile	Periphery - tangential + radial	Root - longitudinal
	Web - " " "	
	Bore - " " "	
High temp. tensile	Same as above	- - - - - - - - - -
Stress-Rupture	Periphery - tangential + radial	Airfoil - longitudinal
Creep	Web - tangential	Root - longitudinal
	Bore - tangential	

One or more parts made by the same process are then qualified by running in experimental engines to demonstrate satisfactory performance.

Process Sheets, which define the basic steps used in the manufacture of the part, are then submitted to P&WA for approval. These sheets commit the vendor to make future parts by the practice used to make the parts which were qualified.

1. Manufacturing Controls

Documentation, which sets forth P&WA requirements in firm, concise terms, is basic to procurement of parts of consistently high quality. The following are the primary documents used by P&WA.

1. The part drawing, which defines the configuration of the part, as well as the material, by means of material and/or process specifications
2. Material and Process Specifications, either AMS (Aerospace Material Specifications) or PWA (Pratt & Whitney Aircraft), which define the chemical, mechanical and metallurgical characteristics required
3. PWA 300, which is a general specification which defines required Laboratory Controls, and forms a part of each Purchase Order for product (engine) parts or material
4. Applicable P&WA Materials Control Laboratory Manual Sections, such as F-3, which defines required Vendor Control of Large Forgings, and F-11, covering Vendor Control of Ferrous and Heat-Resistant Castings
5. Materials Control Laboratory Vendor Agreements, which modify or clarify controls to fit the vendor's situation
6. P&WA Quality Assurance Specifications:

   QA 6071, which establishes general instructions for control and identification of materials and parts

   QA 6064, which defines requirements for suppliers' quality control systems

   QA 6078, requirements applicable to producers of P&WA-designed forgings and castings

Surveillance of all operations, from the melting of metal to final acceptance of the finished part, is a joint responsibility of the Materials Control Laboratory and Quality Assurance.

Materials Control Laboratory personnel regularly visit melting sources in order to approve and monitor procedures for producing alloys for use in critical rotating parts. After thorough evaluation of a vendor's facilities, procedures, organization and personnel, together with testing by P&WA of the vendor's products, P&WA will approve the source. Source approval requires that the ingot source not make any significant changes in equipment, procedure or technique after approval is granted, without written permission from P&WA Engineering Department and applicable forging or casting source prior to the first shipment incorporating such a change. These requirements are formalized by a vendor Agreement, requirements of paragraph H.4.a. Periodic surveillance visits are then made by Materials Control Laboratory Personnel.

Forge shops and foundries making major rotating parts are approved in a similar manner. Controls by P&WA pertaining to evaluation of raw material and product, including frequency of cut-ups, location and number of test specimens, system of identification, record keeping, etc., are detailed in Materials Control Laboratory Manual Sections, as described in paragraph H.4.a. Resident metallurgists and Vendor Quality Control Representatives maintain continuing surveillance over all aspects of the vendor's system for providing quality parts to P&WA.

Development metallurgists continually work with melting, casting and forging sources to improve techniques, resolve questions of interpretation, and, generally, to assure a consistent high-quality product.

Vendor testing of both the raw materials and the finished product is a continuing requirement. Tests required are as detailed in paragraph H.3.a. above. For purposes of periodic destructive testing, forged rotating parts are grouped by metallurgical similarity: one cut-up is required for each twenty (20) pieces produced in each group, or one in each group every four months, whichever results in less testing. JTF17 parts, subject to this type of control of the alloys presently specified, include:

1. Titanium Compressor Disks
2. Waspaloy Compressor Disks
3. Astroloy Turbine Disks
4. Incoloy 901 Hubs

5. Waspaloy Hubs
6. Waspaloy High Compressor Shaft
7. Incoloy 901 Low Compressor Shaft

In addition, a 16-point grain size check is made on each Waspaloy and Astroloy part, and a metallographic study made in selected areas of each cross-sectioned part, using both light and electron microscope, to insure conformance to metallurgical requirements.

Testing of the product by P&WA is used primarily to confirm vendor results, since the burden of proof of conformance is the vendor's. In the case of critical rotating parts, this testing includes non-destructive techniques, such as sonic, fluorescent penetrant and radiographic inspection. Destructive testing of integral test material and periodic vendor cut-ups are also performed as a continuing check on the validity of the vendor's testing.

To assure disk integrity, P&WA employs a unique recording system, whereby all non-destructive testing data is accumulated by heat to provide a complete heat history. By means of entries on Alloy Data Records and Billet Layout Charts, all pertinent information concerning allocation of a heat, by ingot and billet, is presented, together with results of non-destructive tests by both vendor and P&WA. Constant updating of these records, as the parts proceed through manufacturing inspection sequences, permit trained metallurgists to associate defects with specific portions of heats, or entire heats, and thus may warrant rejection of parts otherwise considered acceptable by non-destructive inspections.

Results of all laboratory testing, by both vendors and P&WA, are fed into a Data Retrieval System, which is a specially designed computer program that commits metallurgical, mechanical property, and chemical analysis data to a memory system; and, subsequently, upon command tabulates and, if required, analyzes the data. This system allows trained metallurgists and engineering personnel to evaluate materials quickly. This information is used to upgrade specifications, design criteria, etc.

P&WA experience on supersonic aircraft engines has indicated the necessity for instituting special controls on disks, beyond those imposed on comparable parts for engines in current commercial service. Since each disk is considered basic to engine integrity, the following special controls apply:

1. Integral test specimens <u>from each disk</u> are tested for mechanical properties, generally tensile (room and elevated temperature, plus stress-rupture and/or creep-rupture), by both the Vendor and P&WA. The location of the integral coupon is selected to represent the lowest properties in the disk proper. Deviations from minimum specification requirements are critically reviewed for acceptance or rejection by qualified Materials and Design Engineering personnel.
2. <u>Each disk</u> is subjected to a grain size and/or microstructure check in either the semi-finished or finish-machined configuration. P&WA materials philosophy requires the use of consistent, fine-grained material. Accordingly, standards for grain size and microstructure (Sections E-55 and E-56 of the Materials Control Laboratory Manual) have been established, and are available for review. These require uniform forged recrystallized structure and severely limit the size and distribution of carbides in the grain boundaries. Magnifications of 100X to 10,000X are requi.ed to adequately establish structural details, thus necessitating proficiency in electron microscopy. Examples of the electron microscopic standards are shown in figure 20.

SECTION III
COATINGS SPECIFIED AND DESCRIPTION OF COATING PROCESS

A. INTRODUCTION

P&WA's utilization of coatings to increase the life of turbine blade and vane hardware has been briefly referred to in the introduction to Report F. In both extended TBO commercial engines and military engines, including the high performance J58 (see table 1), coatings have been used to increase life with a high degree of success.

It is important to recognize that the cruise requirements of the JTF17 engine involve thousands of hours at turbine vane and blade metal temperatures which current commercial engine turbine vanes and blades reach only during take off. This fact substantiates the desirability of coating such components of the JTF17 for improved life.

The inability of some of the conventional uncoated superalloys to provide long time service in commercial gas turbines due to oxidation-corrosion is an established fact. This is graphically demonstrated in figure 1 in which one of the more sulfidation resistant alloys, U-700, shows gross deterioration resulting from long time service in one of the P&WA commercial gas turbine engines where cruise turbine temperatures are substantially lower than those of the JTF17 engine.

Subsequent sub-sections delineate (1) the background of P&WA and industry coating developments, (2) the coatings specified on engineering drawings completed in Phase II-C and an explanation of these coatings, and (3) improvements or future development for advancing the protective coating system of the JTF17. All specified coatings are commercially available by reproducible methods; the P&WA specification designated for each coating assures proper control of the application. Service life of the coatings is represented in terms of accumulated engine hours or accelerated hours depending upon the type of data; all of Phase II-C testing was accelerated by using higher temperature to afford completion within the time allotted.

Table 1. Partial Listing of Pratt & Whitney Engines Utilizing Coated Turbine Components

ENGINE	TURBINE COMPONENT	ALLOY/COATING	TOTAL SERVICE EXPERIENCE
J52-P-6, 8A	1st Vane	B-1900/PWA 47	564,300 hours
	1st Blade	B-1900/PWA 47	564,300 hours
JT8D-1, 5	1st Vane	WI 52/PWA 45	2,250,000 hours
	1st Blade	U-700/PWA 47	2,250,000 hours
	2nd Vane	Inco 713/PWA 47	1,000,000 hours
JT8D-7	1st Vane	WI 52/PWA 45	No service experience
	1st Blade	B-1900/PWA 47	No service experience
	2nd Vane	Inco 713/PWA 47	No service experience
JT3D-1, 3	1st Vane	WI 52/PWA 45	10,895,500 hours
JT3C-6, 7	1st Vane	WI 52/PWA 45	6,540,000 hours
TF33-P-7	1st Vane	WI 52/PWA 45	--------------
	1st Blade	B-1900/PWA 47	--------------
TF30-P-1, 6	1st Vane	Mar-M302/PWA 45	2,600 hours flight time
	1st Blade	Inco 713/PWA 47	2,600 hours flight time
	2nd Vane	Inco 713/PWA 47	2,600 hours flight time
	2nd Blade	Inco 713/PWA 47	2,600 hours flight time
TF30-P-3	1st Vane	Mar-M302/PWA 45	2,600 hours flight time
	1st Blade	B-1900/PWA 47	2,600 hours flight time
	2nd Vane	B-1900/PWA 47	2,600 hours flight time
	2nd Blade	B-1900/PWA 47	2,600 hours flight time
	3rd Vane	B-1900/PWA 47	2,600 hours flight time
JT12A-8	1st Vane	WI 52/PWA 45	No service experience
	1st Blade	B-1900/PWA 47	No service experience
J75-P-13B	1st Vane	WI 52/PWA 45	----------------
	1st Blade	U-700/PWA 47	----------------
J57-43, 59	1st Vane	WI 52/PWA 45	No reported service experience.
J58	Coated turbine hardware.		Substantial
		IN 100-MarM200/PWA 47	
		IN 100/PWA 58	
		PWA 664/PWA 64	
		TD Ni/PWA 62	

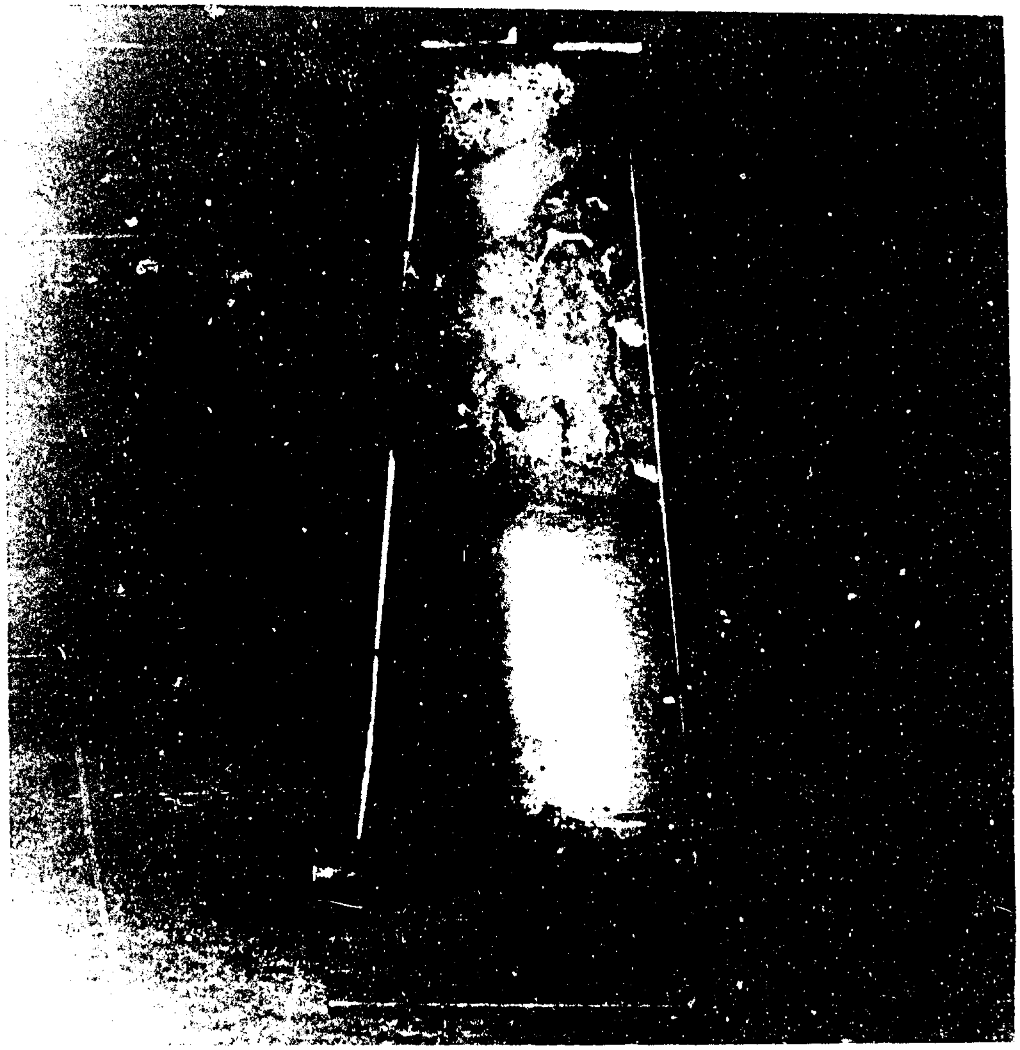

Figure 1. Uncoated U-700 JT3C-6 2nd-Stage Turbine Blade, Removed From a Service Engine, Showing Severe Sulfidation

H-53482
FIII

B. BACKGROUND

The achievement of high strengths and stability in nickel base superalloys for gas turbine applications has generally been obtained at the expense of oxidation-erosion resistance. The basic oxidation resistance of earlier, simpler alloy systems has been compromised by the advent of lower chromium contents in the modern high-strength alloys. For this reason it is desirable to form oxidation-erosion resistant surface alloys (coatings) on hardware.

Aluminide coatings on nickel base superalloys derive their protectivity from the formation of the intermetallic compound, NiAl, which forms an extremely stable and adherent oxide layer, Al_2O_3; this in turn inhibits further oxidation of the system. These coatings are being regularly applied by P&WA to nozzles, burner cans, turbine vanes, and blades for commercial and military aircraft engines to extend overhaul times and reliability.

The gas turbine engine imposes a variety of environmental effects on engine parts which makes desirable the use of protective schemes. Cooling turbine hardware by the use of by-passed air has been effectively utilized in P&WA engines; but since the use of large amounts of cooling air is costly in efficiency and performance, the coating concept can be used to reduce the amount of cooling air used.

The reactions between metals and their environment is a subject which has been embraced by the general term "corrosion". The gas turbine environment is so complex that the term "corrosion" does not provide an adequate description of the metal/environment reactions and can be supplemented by more descriptive terminology. Oxidation, the first recognized degradative phenomenon in the engine environment, is the reaction of metal at elevated temperature with oxygen. Erosion describes the high velocity abrasive effects of dust, carbon particles, and dirt impinging on turbine parts. Gas erosion is the removal of metal and coatings by high velocity gases. Sulfidation is related to complex reactions in the turbine environment involving sulfur in fuels and intake air, chlorine from marine salts in the atmosphere, and metal components, which results in exfoliation of turbine hardware. Overtemperature of parts increases the severity of the foregoing.

Pack cementation, plasma spray, and slurry spray techniques for the application of coatings are the methods most applicable to large scale production. The vendor-developed PWA 45 coating, used on cobalt base alloy turbine vanes is applied by pack cementation which is generally regarded by the aircraft engine manufacturers and coating vendors to be the most reproducible and effective method of producing aluminide coatings. This process for aluminide coatings consists of encapsulating the vane or blade in a retort filled with coating material comprised of a relatively small amount of elemental aluminum powder, modification elements, halide activator, and inert material such as activated alumina. During heating, conversion of the aluminum and modifying elements to gaseous metal halides occurs. These metal halides react with the substrate leaving an aluminum rich surface. This process offers a significant advantage in that normally inaccessible internal passages can be coated as well as the more accessible external surfaces. P&WA developed PWA 64 coating is a very successful example of this process.

PWA 47 is a P&WA developed coating applied by slurry techniques, which offers the advantage for either selectively coating portions of engine hardware or coating hardware too large to be processed by pack cementation. This type coating can be easily modified by the use of prealloyed powders or by mechanically blending coating constituents. The slurry is comprised of metal powders suspended in a lacquer which acts as a vehicle to carry the powders to the work piece and as a binder for the coating in its green state. It is applied by spraying through a nozzle using compressed air. Reaction of the coating with the substrate is usually accomplished during a step in the heat treatment of the base alloy. Plasma spraying consists of passing an inert gas, such as argon, through the electrical arc at high velocity. Coating materials are introduced to the gas stream in powder form. The ionized gases, or plasma, heat the powder particles so that they are plastic and adhere readily to the work piece. Reaction with the substrate is accomplished similarly to slurry coating. P&WA developed PWA 58 is an example of this type of coating.

In search of better coatings, P&WA actively solicits and evaluates coatings developed by the coating industry. Table 2 provides a comparison of vendor-developed coatings with in-house coatings.

Nonmetallic ceramic coating systems are being used increasingly on hardware requiring thermal insulation and wear resistance, as well as oxidation-erosion resistance. The technology of nonmetallic systems is not as sophisticated as it is for the metallic diffusion coatings. The poor impact and thermal shock capabilities of most oxides, as well as the difficulty in producing a reliable ceramic-to-metal bond, has been a substantial deterrent for their use as coatings in the past. On the other hand, the thermal insulative qualities and excellent resistance to particle erosion of ceramics are qualities too attractive to be overlooked. P&WA has developed and has utilized ceramic coatings to excellent advantage on such hardware as afterburner flaps, burner cans, liners, and transition ducts.

Techniques developed in the laboratory for the application of ceramic coatings include plasma spraying, oxy-acetylene spraying and slurry techniques. More sophisticated methods, such as vapor deposition and deposition by electrophoresis of ceramic and cermet coatings, offer promise for future application.

Table 2. P&WA/Vendor Coating Evaluation on Nickel Base Alloys (Accelerated Testing)

Substrate Alloy	Coating Designation	Coating Vendor	Oxidation-Erosion Test Rating* 100 hours, JP-5 Fuel 2000°F	2100°F
Mar-M200	UC	Chromalloy	A	C
Mar-M200	UD	Chromalloy	C	-
Mar-M200	C-6	Haynes Stellite	C	-
Mar-M200	C-9	Haynes Stellite	C	C
Mar-M200	MDC-6	Misco	B	A
Mar-M200	Aluminum	Misco	C	-
Mar-M200	Aluminum	Sylcor	C	A
Mar-M200	IAD	Whitfield Lab	A	-
Inco 713	Aluminum	Misco	C	-
Inco 713	MDC-6	Misco	B	-
Inco 713	Aluminum	Sylcor	B	-
Inco 713	IAD	Whitfield Lab	C	-
Inco 713	II Cad	Whitfield Lab	C	-
Waspaloy	Aluminum	Sylcor	C	-
U-700	Aluminum	Misco	B	-
U-700	Aluminum	Sylcor	C	-

*Rated relative to PWA 47 coating performance

A = Better than

B = Equal to

C = Poorer than

Table 2 - Continued. P&WA/Vendor Coating Evaluation on Ni-Base Alloys (Accelerated Testing)

Substrate Alloy	Coating Designation	Coating Vendor	Oxidation-Erosion Test Rating* 100 hours, PWA 523 Fuel 2100°F
Mar-M200	PWA 47	PWA	-
Mar-M200	PWA 58	PWA	B
Mar-M200	PWA 64	PWA	A
Mar-M200	Udimet	TRW	B
Mar-M200	SAC	Chromalloy	D
Mar-M200	MOT	Chromalloy	D
Mar-M200	X10650	Chromalloy	D
Mar-M200	Cr-Al	Alloy Surface Co.	C
IN 100	PWA 47	PWA	-
IN 100	PWA 58	PWA	A
IN 100	PWA 64	PWA	A
IN 100	C-20	Haynes Stellite	D
B-1900	PWA 64	PWA	A
B-1900	PWA 58	PWA	A
B-1900	PWA 47	PWA	B
B-1900	MOT	Chromalloy	D
B-1900	X10650	Chromalloy	D

* Rated relative to PWA 47 coating performance

A. Better than

B. Equal to

C. Poorer than

D. Failed

Table 2 - Continued. P&WA/Vendor Coating Evaluation of Cobalt Base Alloys (Accelerated Testing)

Substrate Alloy	Coating Designation	Coating Vendor	Oxidation-Erosion Test Rating* 100 hours, JP-5 Fuel 2000°F	2100°F
WI 52	MDC-7	Misco	A	C
WI 52	Chromium	Alloy Surfaces	-	C
WI 52	Calorize	Calorizing Corp.	-	B
WI 52	Aluminum	Calorizing Corp.	A	-
WI 52	C-12	Haynes Stellite	C	C
WI 52	SAC	Chromalloy	A	C
WI 52	UD	Chromalloy	A	C
WI 52	IAG + Al	Whitfield Lab	-	C
Mar-M302	SAC	Chromalloy	B	A
Mar-302	UD	Chromalloy	C	A
Mar-M302	PWA 47	PWA	C	B

* Rated relative to Chromalloy UC coating performance

A. Better than
B. Equal to
C. Poorer than

Table 2 - Continued. P&WA/Vendor Coating Evaluation of Cobalt Base Alloys (Accelerated Testing)

Substrate Alloy	Coating Designation	Coating Vendor	Oxidation-Erosion Test Rating* 100 hours, PWA 523 Fuel $2100^{\circ}F$
Mar-M302	PWA 59	PWA	A
Mar-M302	UC	Chromalloy	-
Mar-M302	SAC	Chromalloy	A
Mar-M302	#208	Misco	D
Mar-M302	PWA 47	PWA	B
Mar-M302	C-3	Haynes Stellite	D
Mar-M302	C-6	Haynes Stellite	D
Mar-M302	C-12	Haynes Stellite	C
Mar-M302	C-20	Haynes Stellite	D
WI 52	Udimet	TRW	D
WI 52	C-12	Haynes Stellite	C
WI 52	C-20	Haynes Stellite	D
WI 52	PWA 59	PWA	A
WI 52	UC	Chromalloy	-
WI 52	SAC	Chromalloy	C

* Rated relative to Chromalloy UC coating performance.

A. Better than
B. Equal to
C. Poorer than
D. Failed

C. SPECIFIED COATINGS FOR THE JTF17

1. PWA 64 Coating on PWA-658 (IN 100) Turbine Blades and Vanes

Investment cast PWA-658 (IN 100) turbine blades and vanes have been used with success in the J58 engine providing dependable service. These parts have evolved through significant improvements in casting practice and chemistry modification programs.

The oxidation characteristics of PWA-658 (IN 100) alloy have been thoroughly investigated in both laboratory studies and after service in the turbine environment. The oxidation resistance of the alloy is surprisingly good in a high velocity oxidizing gas stream at temperatures up to 2200F even though there is only 9% chromium in the alloy. Even so the alloy should be coated for longer life JTF17 service. The 1st, 2nd and 3rd stage turbine blades will experience maximum local metal temperatures of 1650F, 1660F and 1575F, respectively.

The 2nd and 3rd stage turbine vanes will experience maximum local metal temperatures of 1640F and 1540F, respectively, which are well below the temperature limitation for aluminum base diffusion coatings, therefore, they were selected. In considering the limiting coating characteristics which govern successful performance, the following were thoroughly investigated in sequence:

1. Oxidation rate of the beta nickel aluminide as modified by coating and base metal constituents at temperatures up to 2200F
2. Hot gas and particle erosion rates of the adherent oxide film formed on the coating surface
3. Hot corrosion resistance under conditions more severe than those of the JTF17
4. Coating/base metal interface melting point
5. Effect of the coating on base metal mechanical properties
6. Foreign object damage and impact resistance of the coating
7. Possible effects of sigma-like formations at the coating/base metal interface.

It was felt that diffusional stability would be of little or no c n at the intended service temperature in this application. This contention was substantiated by microstructural investigation of coated creep rupture test specimens with over 3000 hours exposure at 1600F. A change in total coating thickness of less than 10% was observed after this testing. On the basis of the foregoing criteria, one coating was selected as possessing the optimum combination of characteristics. The coating, designated PWA 64, is a chromium-magnesium modified aluminide coating. Pack cementation was chosen for the application of PWA 64 because it is economical and reproducible, and it is th only reliable means for coating interior cooling air passages.

The basic aluminide coating system was modified to reduce the amount of aluminum required for the production of the protective Al_2O_3 layer. The lower aluminum content in the coating results in greater ductility, increased resistance to thermal fatigue, and increased resistance to erosion. This greater ductility also allows heavier coating thickness for extended life. The modified coating has greater resistance to sulfidation and hot corrosion than any of the other systems evaluated.

The small amount of magnesium in the coating oxidizes preferentially in service to form MgO which combines with Al_2O_3 layer. This reaction effects increased bond strength between the protective Al_2O_3 and the coating, thereby promoting increased scale retention and longer service life. A complete coating evaluation of the PWA-658/PWA-64 system has revealed the following characteristics:

1. The oxidation of PWA-64 on PWA-658 (IN 100) substrate is negligible at 1800°F in over 800 hours exposure with tests still in progress.
2. The erosion resistance of the PWA 64/IN 100 system has been studied in accelerated oxidation erosion tests using aviation kerosene at 1800°F with no evidence of coating degradation after 900 hours. These tests still are in progress.

3. Sulfidation testing using 0.3% sulfur in aviation kerosene with 1 ppm synthetic sea salt aspirated in the combustion stream shows the coating unaffected after 1200 hours at 1800°F in accelerated testing. (Testing in progress - see figure 2). The capability of the coating at 1600°F is good in this environment.

4. PWA-64 causes no detrimental effect on the creep rupture strength of PWA-658 (IN 100) in the section thickness involved in this application.

5. A stripping technique has been developed that will enable reprocessing of PWA-658 (IN 100) vanes. Stripping and recoating PWA-658 (IN 100) vanes causes no adverse effect on service ability.

6. Coating ductility at 1600°F is excellent. This has been observed in the response of the coating to severe localized impact damage and the ability of the coating to "bridge" over intergranular thermal fatigue cracks or fissuring on creep rupture specimens. In these localized areas the coating has frequently "necked down" showing a good degree of ductility.

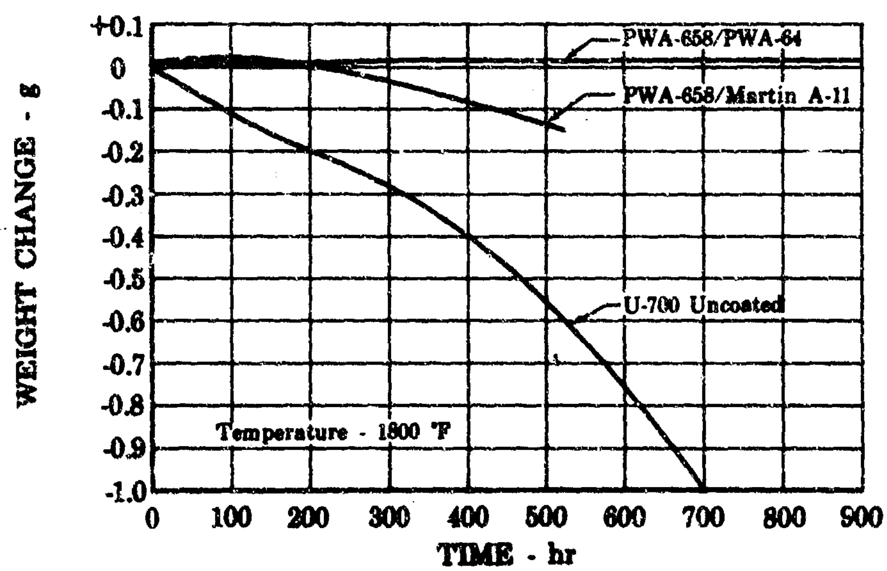

Figure 2. Accelerated Sulfidation Behavior of Coated PWA-658 Compared to Uncoated U-700

FD 16888
FIII

It is fully expected that PWA-64 will provide reliable long time protection for PWA-658 (IN 100) turbine vanes in this application.

2. PWA 62 Coating on PWA 1035 (TD Nickel) First Stage Turbine Vane

The use of dispersion hardening as an effective strengthening mechanism for high temperature alloys has been realized in recent years through the development of PWA-1035 (TD Nickel). This alloy has been received enthusiastically in the aircraft gas turbine industry and has been studied by P&WA in the areas of fabricating and joining practices, mechanical property evaluation, and response to environmental effects at elevated temperature. Several areas of application are presently under test in P&WA engines. The use of the alloy in the sheet form as a fabricated turbine vane is being tested in the J58 and other engines. The advantage of this alloy include the following:

1. High melting point. This property is desirable because it provides a substantial safety margin for vane burnout during accidental hot starts in engine operation.

2. High thermal conductivity. This characteristic keeps thermal gradients to a minimum and, therefore, improves thermal fatigue and reduces maximum "hot-spot" temperature.

3. Good elevated temperature creep strength of the alloy will provide resistance to trailing edge bowing.

4. The fact that PWA-1035 (TD Nickel) forms an adherent protective nickel oxide film.

Engine testing in the J58 engine and laboratory investigations of the oxidation characteristics of PWA-1035 (TD Nickel) have shown that for long time turbine vane application at metal temperatures of 1800°F and higher, it is desirable to have a protective coating. Surprisingly, the alloy has shown only mildly increased scaling rates in a very corrosive simulated turbine environment at metal temperatures up to 2000°F.

P&WA in early 1963 recognized the fact that for either very long time service or metal temperatures in excess of 2000°F, the alloy would require coating. A coating development program was undertaken at that time which has eventually led to the duplex pack coating currently employed on J58 experimental PWA-1035 (TD Nickel) vanes. The coating, designated PWA-62, involves the application and simultaneous diffusion of pure chromium at temperatures and concentrations that enable the formation of a nickel-chromium (40-45% chromium) surface alloy. This surface is packed coated with an aluminum-chromium alloy. The resultant ternary surface composition possesses some exceptional characteristics. This complex process was evolved after considering that conventional aluminum metallic diffusion coatings are rapidly dissolved in PWA-1035 (TD Nickel) at temperatures far below their intended service temperature. The diffusion rate of aluminum in unalloyed nickel is high and nickel provides a very effective "sink" for rapid equalization of any large compositional gradient. It was frequently observed that differential diffusion rates would cause extreme coating/base metal interfacial porosity (Kirkendall Effect) and would result in gross spalling failure of the coating. It is interesting to note that since this phenomenon is a diffusion controlled process, coatings would occasionally show extensive interface porosity in the as-coated condition, depending upon pack concentration, processing time and temperature.

The initial chromium coating serves to inhibit gross diffusion of nickel and aluminum, prevent porosity, and, therefore, prolong the life of the coating by providing a reservoir of aluminum to replenish that lost on the surface through oxidation.

Pertinent coating characteristics are presented below:

1. PWA-62 coated PWA-1035 (TD Nickel) shows no deterioration in over 200 hours of high velocity, high temperature gas erosion at a metal temperature of 2200°F in accelerated environmental testing. This is one hundred degrees better than most superalloy/coating combinations known. Accelerated sulfidation testing at 1800°F using 0.3% sulfur in aviation kerosene shows no coating distress in 600 hours (tests still in progress - see figure 3). Maximum expected metal temperature in the JTF17 engine is 1700°F.

2. The melting point has been determined to be in excess of 2400°F.

3. Diffusional stability of the system is sufficiently high to enable as high as 1800°F service for a minimum of 3000 hours.

4. Mechanical property evaluation and engine test experience have shown that the coating has no detrimental effect upon the creep strength of the alloy.

5. The coating has doubled the thermal fatigue capability of PWA-1035 (TD Nickel) sheet vane airfoils for the J58 engine at a test temperature of 2200°F.

6. Pack coatings are ideal for the coating of internal passages. Static oxidation of the internal surface on PWA-1035 (TD Nickel) airfoils has virtually been eliminated.

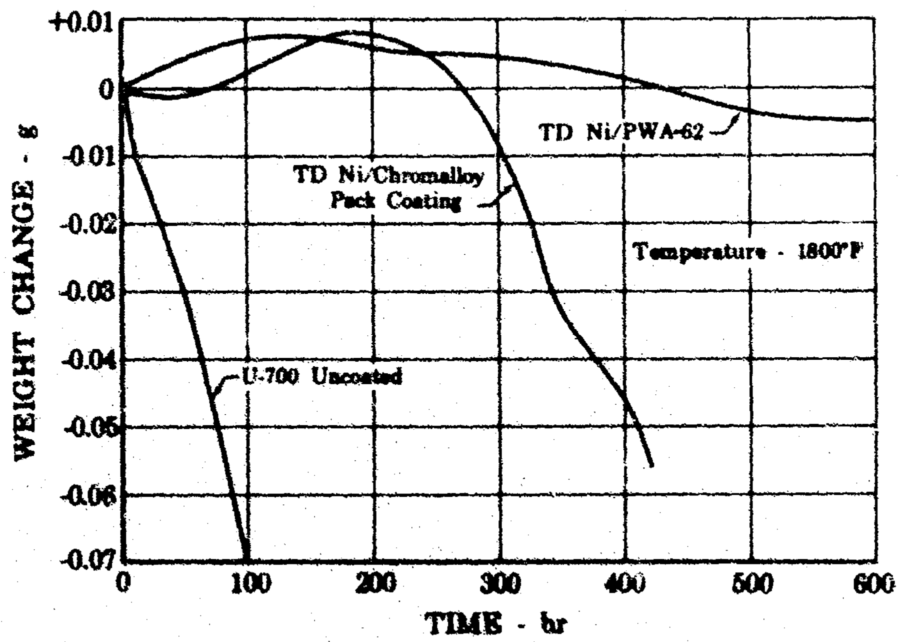

Figure 3. Accelerated Sulfidation Behavior of Coated TD Nickel Compared to Uncoated U-700

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FIII

The combination of excellent elevated temperature strength of PWA-1035 (TD Nickel) and the high temperature capability of the PWA-62 coating is expected to provide good performance for the 1st stage turbine vane in the JTF17 engine.

3. PWA-64 Coating on PWA-664 Turbine Vanes and Blades

PWA-664 has been selected as the alternate 1st stage turbine vane alloy and a proposed turbine blade alloy. The P&WA developed coating for PWA-664, designated as PWA-64, is the chromium-magnesium modified aluminide coating detailed in Section C-1. As previously mentioned the pack cementation application technique lends itself to the coating of fairly complex shapes and to high volume production.

The decision to utilize aluminide coatings was the result of previous experience with this class of coating at the service temperatures of the JTF17 turbine blades.

Complete evaluation of the PWA-664/PWA-64 system has revealed the following significant coating characteristics:

1. Accelerated testing of PWA-64 coated PWA-664 showed no deterioration in over 200 hours of high velocity, high temperature combustion gases at a metal temperature of 2100°F. Further accelerated testing at 1800°F under similar environmental conditions showed no coating distress in over 1000 hours of testing.
2. Accelerated sulfidation testing using 0.3% sulfur in aviation kerosene with 1 ppm synthetic sea salt aspirated into the combustion gases shows the coating unaffected after 1200 hours at 1800°F. This test is still in progress. (See figure 4.)
3. PWA-64 causes no detrimental effect on the bow resistance and creep rupture properties of PWA-664 in the section thicknesses involved. This has been substantiated in experimental engine testing.
4. Microstructural studies of the coating structure have shown that the coating possesses excellent diffusional stability and will retain its usefulness for the duration of anticipated service.
5. The ability of the coating to be stripped and reapplied to used hardware has been demonstrated and shown to create no ill effects from a serviceability standpoint. This is particularly valuable for commercial engine service where reuse of costly parts at overhaul can result in a significant savings in over-all operating cost.

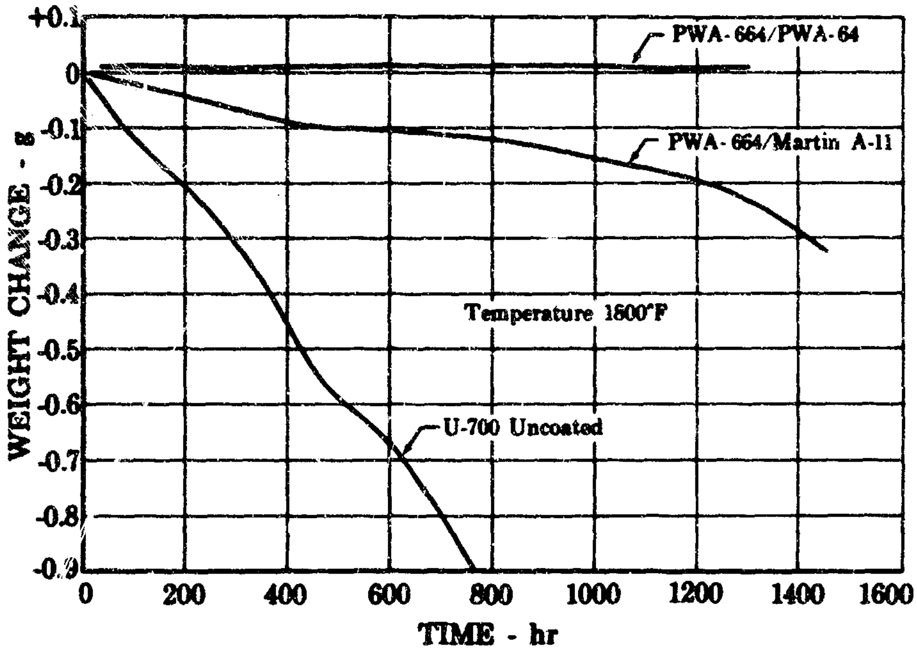

Figure 4. Accelerated Sulfidation Behavior of Coated PWA-664 Compared to Uncoated U-700 — FD 17018 FIII

This blade-coating system comprises the best turbine blading for aircraft gas turbines seen to date based upon the elimination of transverse cracking caused by thermal fatigue, superior bow resistance and creep strength, and long term oxidation-erosion-sulfidation resistance.

D. ADVANCED COATING DEVELOPMENT PROGRAMS FOR THE JTF17

1. Improved Metallic Coatings

Improvement of metallic diffusion coatings to extend service lives, reliability, and permit higher turbine inlet temperatures requires a definitive understanding of the formation, structure, composition, and failure modes of these systems. Representative samples in the as-coated, heat treated, and oxidized conditions are studied to provide insight into the various phase transformations occurring during coating formation and subsequent use. The procedures used for phase identification and analyses include optical metallography, electron metallography, microhardness measurement, electron probe micro-analysis, and X-ray diffraction.

Optical and electron microscopy is instrumental in determining the general integrity of a coating structure and in locating areas of interest for more detailed investigation. Specimens are examined in the unetched condition, then etched to develop the phases present in both coating and substrate. Selective etching is employed to differentiate between phases present. Figure 5 illustrates a typical microstructural study of a nickel base alloy/coating system. Microhardness measurements of coatings and substrates are made. Specimens are metallographically polished and etched prior to testing. These tests provide insight into the relative ductility and toughness of coating systems and aid in phase identification. Distributions of the major elements (Ni, Al, Co, W, Cr, Si, and Ti) in coatings and substrates are determined with an electron probe microanalyzer. Qualitative analyses of phases are obtained from electron backscatter and X-ray images over areas representative of the microstructure. Relative concentrations of the elements are shown by the contrast of light and dark areas in the X-ray images. Quantitative analyses of phases are obtained by mechanically scanning the beam across the coating-substrate composites. Chart-recorded concentration profiles, exhibiting both peak and background intensities, are obtained from the phases traversed and from elemental standards (figure 6). Standard X-ray diffractometer techniques are also employed for phase identification in the coatings and for identification of oxidation and corrosion products.

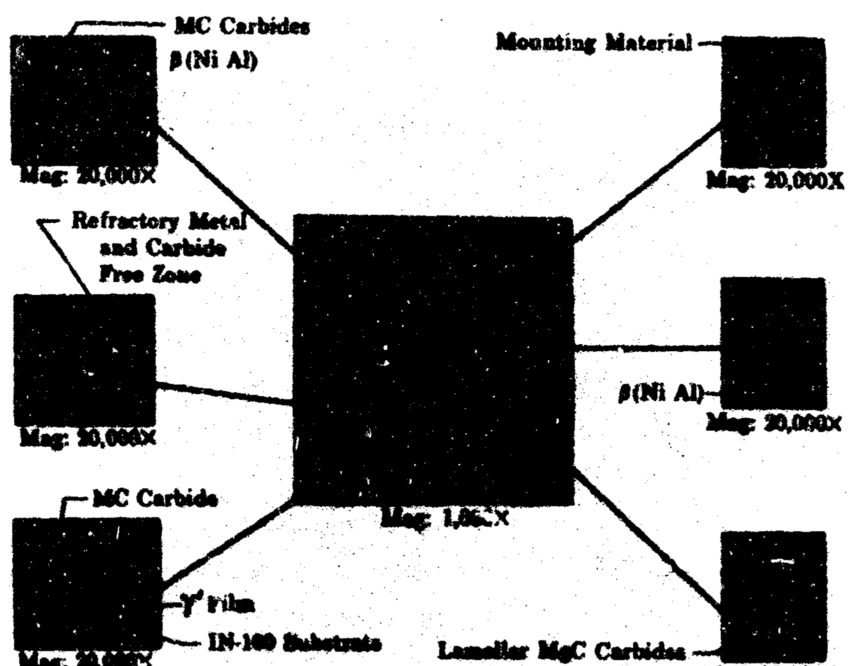

Figure 5. Microstructural Study of the PWA-658/PWA-58(T-3) System

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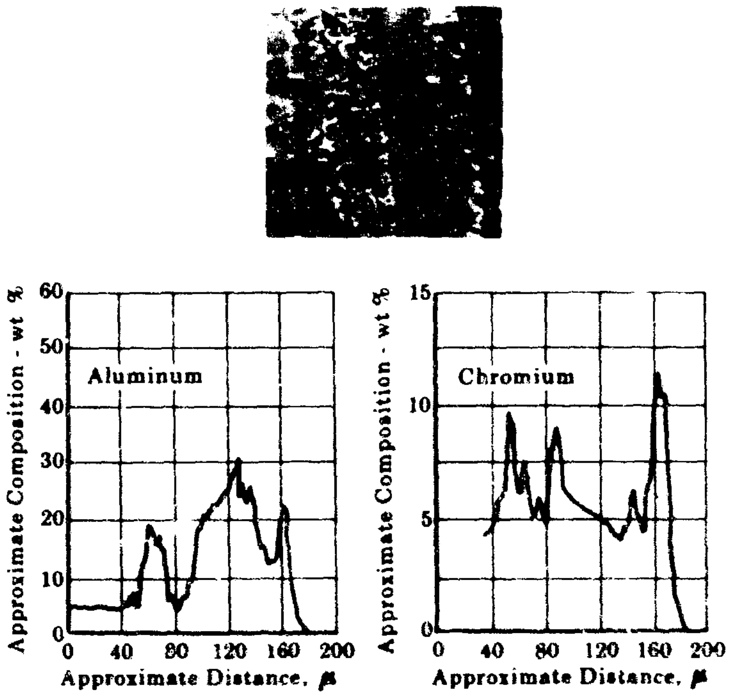

Figure 6. Composition Profiles of PWA 64 Coated PWA 664 (As Coated)   FD 16667 FIII

Based on knowledge largely developed by P&WA with the aid of such instruments mentioned above, the possible modes of coating degradation in the nickel-aluminide coating system can be delineated.

a. Oxidation degradation:

(1) oxidation of the beta (NiAl) phase to form a protective layer of Al_2O_3

(2) loss of this protective layer, necessitating its continuous reformation by consumption of aluminum from the beta (NiAl)

(Ni_3Al) and eventually to gamma (Ni-Al solid solution)

(3) and finally, consumption of the aluminum from the three phase system.

b. Erosive degradation:

(1) removal of the protective layer of Al_2O_3 by high velocity particles thereby accelerating oxidation

(2) physical removal of the metallic coating layer by high velocity particles in the gas stream.

c. Thermal shock effects:

(1) spalling of the protective Al_2O_3, thereby accelerating oxidation

(2) spalling of the metallic coating layer

(3) thermal fatigue cracking of the coating-substrate system, thereby causing failure by a combined oxidation-crack propagation process.

Sulfidation constitutes another dimension of coating degradation. The mechanisms of this form of deterioration are under intensive study in current development programs for the improvement of coating systems for advanced engine applications.

The theories of degradation derived from these studies provide the basis for new coating concepts designed to minimize or prevent the modes of failure for most contemporary aluminide coatings. The results of these programs sponsored by the J58 engine are directly applicable in the JTF17 engine.

Improvement of oxidation-erosion-corrosion resistance has largely been accomplished through modification of the basic aluminide coating by the addition of beneficial elements. PWA-47 for instance, is an aluminide coating, applied by slurry, which has been modified by the addition of silicon. Other coatings developed by P&WA include PWA-64, chromium-magnesium modified aluminum pack coating; PWA-58, tungsten modified plasma sprayed coating: and PWA-62, duplex Cr/Cr-Al coating for PWA-1035 (TD nickel).

Programs are now in progress to modify the structure of contemporary aluminide coatings to obtain further improvements in their capabilities. Major emphasis is being placed on various additives to enhance protective oxide adherence and allow the use of lower aluminum contents in the coating. For example, it has been found that the presence of chromium in aluminum base coatings decreases the amount of aluminum required to form the protective oxide layer thereby increasing the durability of the system and increasing the ability of the coating to withstand thermal shock and impact. As a point of interest, chromium in aluminide coatings has proved to be very beneficial for resistance to hot corrosion and sulfidation. Chromium was used successfully as a primary layer in the PWA-62 duplex coating developed by P&WA for TD nickel to minimize Kirkendall effect at the coating basis-metal interface.

While it is possible to prepare coatings which are extremely oxidation resistant under isothermal conditions, thermal cycling may still rupture and spall the protective oxide layer and significantly shorten the life of these materials. It has been known for some time that the addition of minor amounts (1% or less) of reactive metals such as scandium and other rare earths, to some alloys decreases or eliminates this spalling effect and thereby increases useful life under cyclic oxidizing conditions. Based on laboratory results, the addition of these elements offers promise for use in coating systems.

Of major importance in the improvement of coating/alloy systems is the means by which various systems are evaluated. Although the ultimate evaluation of a coating for a gas turbine environment requires testing in an engine, meaningful research must be done under controlled laboratory conditions. Furnace oxidation tests are employed in preliminary evaluation of the oxidation resistance of prospective coatings. Diffusional stability and melting point determinations for development coatings are established in controlled atmospheric furnaces. Oxidation-erosion tests are conducted using simulated airfoil shaped specimens rotated in front of a jet fuel test burner with flame velocities up to 1100 ft/sec (figure 7). Temperature is optically measured on the outer surface of the rotating specimens. Specimens are removed from the test periodically for visual examination and weight change measurements. The curves of figures 2,3, and 4 are based on data generated in these accelerated tests.

Sulfidation and hot corrosion tests are accomplished in the burner rigs by modifying the chemistry of the exhaust products and by the use of fuels that contain elements which are associated with sulfidation and corrosion problems. High velocity impact and particle erosion tests are also performed on the burner rigs

Oxidation-erosion-sulfidation tests are accelerated by employing metal test temperatures in excess of design temperature for a given turbine part. This provides an effective means for screening prospective

Figure 7. Burner Test Rig Used for Oxidation, Corrosion and Erosion Studies H-53482 FIII

metal/coating systems. Those coatings showing promise in accelerated testing are then subjected to design temperature levels to provide design data. Data from engine testing is correlated with erosion rig information.

The use of metallic coatings in current turbine engines serves to illustrate the potential for improved coatings in advanced engines, and new coating concepts are being explored at P&WA.

2. Cladding

Aluminide coatings are satisfactory in contemporary gas turbine engines and provide reliable protection for the variety of service conditions imposed on them. However, the increasing demands of advanced engines is approaching the limit of capability of conventional metallic diffusion coating systems. Even though improvements in coatings are forthcoming, looking ahead to the highly advanced engines of the 1970's, new and novel protective systems for gas turbine alloys must be developed to keep pace with advanced design. As an illustration, the JTF17 engine requires a service life capability far greater than that required of the J58 engine. The situation is further aggravated by the fact that this engine will operate in a more sulfidation-promoting environment. While conventional coating systems have been improved to meet the more strenuous demands of the JTF17 engine, the advanced JTF17 engines of tomorrow will require improvements in protective schemes over those used today. Of necessity, any new system of protection should possess the following characteristics:

1. Insensitivity to hot corrosion and sulfidation
2. High oxidation-erosion resistance
3. Compatibility of the system and substrate
4. Sufficient ductility to withstand impact and particle erosion
5. High melting point
6. Low interdiffusion rates with substrate alloys

There are a number of alloys available that possess these qualities but lack sufficient strength by themselves for use as turbine hardware structural materials. The obvious implication is that a composite structure composed of a load bearing high strength alloy, such as TD nickel, IN 100, PWA-664, etc., with a cladding of the system as mentioned above would have the necessary characteristics required for long time service. An important advantage of the cladding concept is that thickness can be tailored to meet service requirements.

Current development work includes three avenues of approach to effect the cladding of an airfoil shape. These are as follows:

1. Co-extrusion cladding of hollow or solid airfoil shapes of either constant or varying chord.
2. Cladding a preformed sheet to the airfoil of a cast vane or blade.
3. The use of plasma spraying or vacuum sputtering for deposition of the cladding alloy.

The extrusion cladding practice has received the most attention in P&WA development efforts because of the inherent quality of the metallurgical bond produced, the integrity of the structure of the protective layer, and the simplicity of the concept.

The successful extrusion of clad IN 100 and TD Nickel has already been accomplished. The extrusion-cladding concept can be applied with equal ease to any extrudable superalloy. Figure 8 shows an extruded binary combination of a cladding material and nickel base superalloy.

Diffusional stability tests have shown that the service life capabilities of this system extend far beyond that required by the JTF17 engine.

On blade and vane airfoils, sulfidation and oxidation-erosion tests show that cladding offers protection distinctly better than conventional aluminide coatings. A clad IN 100 test specimen is currently undergoing accelerated sulfidation testing at 1800°F and remains completely inert to the test environment after 2500 hours. (See figure 9)

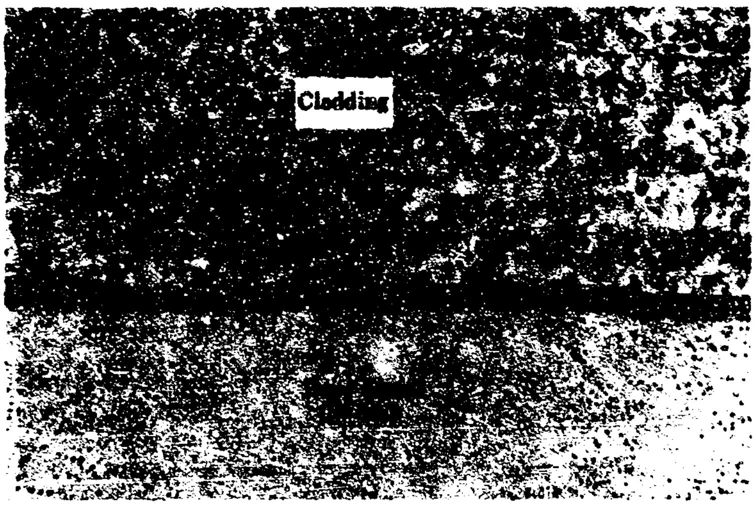

Figure 8. Nickel Base Superalloy Clad by Extrusion with an Oxidation-Erosion-Sulfidation Resistant Alloy Cladding — FD 16671 FIII

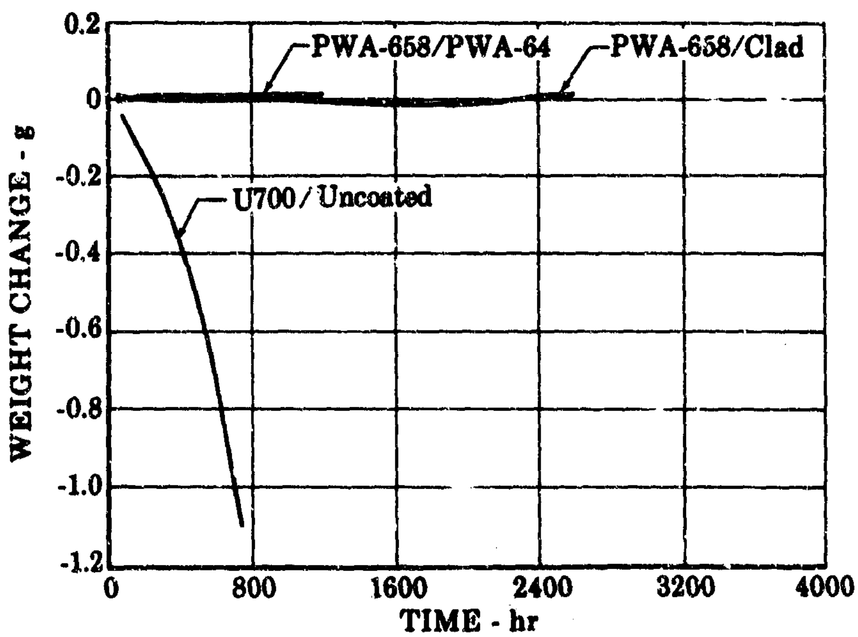

Figure 9. Accelerated Sulfidation Testing at 1800°F — FD 16710 FIII

Specimens clad by plasma deposition of cladding alloy powders are now undergoing oxidation-erosion-sulfidation tests with encouraging results. In the near future, specimens clad by vacuum sputtering deposition will be available for test.

The extrusion program was originally established and designed to consider IN 100 and TD nickel as vane alloys. However, the success of the cladding program has given rise to a number of novel concepts which could enable the use of refractory alloys for future engine applications.

The concept of extrusion cladding turbine vanes and blades offers extremely attractive possibilities; the material combinations under study offer potential for J58 and JTF17 engines and already have shown superiority over all the metallic diffusion coatings presently employed for protection against the gas turbine environment.

3. Nonmetallic Systems

There has been little serious consideration given to the use of mechanically or chemically bonded ceramics as protective coatings for turbine components. For several years, plasma or flame sprayed coatings have been employed as thermal insulators on afterburner components where gas flow has, for the most part, been parallel to the coated surface. Under conditions where direct hot gas impingement or impact damage seemed imminent, the designer has been justifiably reluctant to call for conventional ceramic or cermet coating due to the brittle nature of these materials.

Ceramic coatings are receiving growing interest for gas turbine components and development programs are underway within P&WA. The following characteristics make the materials attractive for this application:

1. Most ceramic oxides possess excellent chemical stability in the oxidizing and corrosive environment of the gas turbine engine.
2. The melting point of the refractory oxides is well above normal service temperatures.
3. From a diffusion or interaction standpoint, most base metal/oxide combinations are stable at the temperatures involved in this application.

4. Repairability is excellent. Complete coating removal may be accomplished readily by standard chemical or mechanical means. Recoating by plasma, flame spraying, or slurry spraying techniques are standard shop practice.

Development efforts have been focused on coating/base metal bond strength. This is the problem area most responsible for premature spalling failure under impact or rapid thermal cycling conditions. Graded metal-ceramic combinations have been employed with considerable success by minimizing the mismatch in thermal expansion characteristics. Chemical bonding of fusible ceramics is presently under study to provide improved bond strength. The concept of graded ceramic coatings is being thoroughly investigated. (See figure 10.) Turbine vanes coated with selected systems have been run with success in the J58 at temperatures over 2000°F. No impact damage on vane leading edges has been observed on any system tested with the coatings affording complete oxidation-erosion protection to the vane airfoils.

This development will continue to be actively pursued. The success enjoyed thus far and the very attractive properties available in the ceramic portend significant developments for the immediate future with this class of coating.

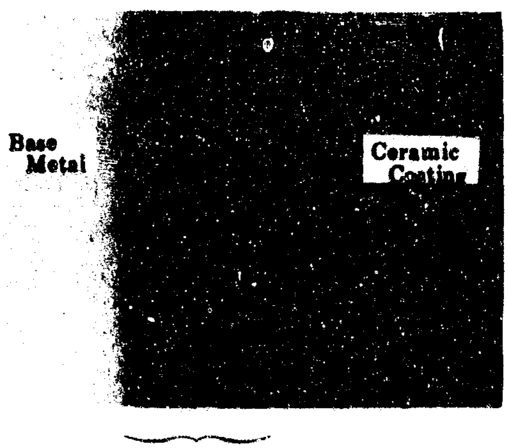

Figure 10. Graded Ceramic Coating Showing Transition From Metal to Ceramic Which Alleviates Thermal Expansion Mismatch and Promotes Chemical Bonding to Substrate

FD 16672
FIII